



Handbook on Climate Change and Agriculture

Edited by **Ariel Dinar** and **Robert Mendelsohn**



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HANDBOOK ON CLIMATE CHANGE AND AGRICULTURE

Handbook on Climate Change and Agriculture

Edited by

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and

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Cheltenham, UK • Northampton, MA, USA

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Published by
Edward Elgar Publishing Limited
The Lypiatts
15 Lansdown Road
Cheltenham
Glos GL50 2JA
UK

Edward Elgar Publishing, Inc.
William Pratt House
9 Dewey Court
Northampton
Massachusetts 01060
USA

A catalogue record for this book
is available from the British Library

Library of Congress Control Number: 2009930434



ISBN 978 1 84980 116 4 (cased)

Typeset by Servis Filmsetting Ltd, Stockport, Cheshire
Printed and bound by MPG Books Group, UK

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Acknowledgments

This book benefited from financial support by the Water Science and Policy Center at the University of California, Riverside and by the Multi-state Research Project W-2190.

We would like to acknowledge the excellent constructive review comments to the various chapters of the book by our reviewers: Lisa Ainsworth, Marcel Aillery, Maximilian Auffhammer, Netra Chhetri, Harry deGrotter, Andrew Dorward, Bruce Dixon, Josef Eitzinger, Rashid Hassan, Ken Hubbard, Brian Hurd, David Kelly, Mary Beth Kirkham, Leslie Lipper, David Lobell, David Maddison, Susanne Nuebert, Dan Osgood, Stefano Pagiola, K.P. Rao, Ron Sands, Daniel Sumner, James Thurlow and Jinxia Wang.

The book also benefited from the in-house editorial work by J. Aapris Frisbie, who carefully checked each chapter for consistency and compliance with the publisher's template.

Finally, we thank Edward Elgar Publishing for their support in this endeavor.

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1 Introduction

Ariel Dinar and Robert Mendelsohn

This book focuses on the impact of climate change on agriculture and how agriculture is able to adapt to such change. It explores what many disciplines can tell us about two questions: what will be the impending impact of such change? and what mechanisms can be implemented to help mitigate the resulting impacts? Climate change is expected to affect human livelihood, to different extents, at different locations. However, the impact on agriculture and its ability to adapt varies a great deal between regions (Mendelsohn and Dinar, 2009a). For example, some countries in Africa already face extreme climatic conditions, whereas some countries in Latin America appear to be the most vulnerable to climate change scenarios (Mendelsohn and Dinar, 2009a). Agriculture is the most important climate-sensitive sector in the economy, contributing 5 per cent of GDP (US CIA, 2011). At present, nearly one third of the earth's land is utilized for growing both crops and pasture (FAO, 2006). Furthermore, farming provides the livelihood of hundreds of millions of people. Three-quarters of the rural poor in developing countries depend on agriculture as their main source of livelihood (IPCC, 2007).

Agricultural and agro-ecological systems in many low-latitude countries are particularly vulnerable for several reasons. (a) climates in many low-latitude countries are already too hot and often too dry; (b) water supplies in these countries are limited and variable; (c) soil quality is often low and degraded; and (d) there is lack of adaptive capacity because these regions are relatively poor, have low levels of technology and R&D as well as weak government institutions.

Therefore it is no wonder that there has been a nexus of agriculture and climate change studies in recent years (e.g. FAO, 2007; Dinar et al., 2008; Nelson et al., 2009; Mendelsohn and Dinar 2009a, b; and Hillel and Rosenzweig, 2011). The FAO (2007) study assembles information and results from many previous studies to arrive at a consolidated assessment of impacts, data and analytical needs, and prescribed directions of policy work. Dinar et al. (2008) apply two methodologies to a set of countries in Africa, namely the production function and the Ricardian methodologies, in order to assess the impact of climate change and adaptation strategies at the country and regional levels. This work focuses on economic and simple agronomic tools. Nelson et al. (2009) deal with cropped agriculture, using a crop growth model in combination with a global agricultural production decision model. The work is focused on normative assumptions and does not explain the relationships between climate change and agricultural impacts. Mendelsohn and Dinar (2009a) combine science and economics to provide a very detailed set of applications of the Ricardian method to crops and livestock in 22 countries. Hillel and Rosenzweig (2011) provide a very comprehensive set of works that focus on the science of climate change and agro-ecosystems. Their study is a nice supplement to this *Handbook on Climate Change and Agriculture* in that it provides valuable scientific background to help understand the complicated interactions between climate change and agricultural production.

So, why do we need another study on climate change and agriculture? The *Handbook* extends previous work by adding the economic and policy context to agronomic and hydrologic analyses. It also demonstrates various methodologies and approaches used by scholars to estimate impacts and adaptation options.

AGRONOMIC STUDIES OF CLIMATE IMPACTS AND ADAPTATION

This part of the book introduces readers to the scientific background that links climate and crops and livestock, crop modeling and drought studies. Ziska (Chapter 2) addresses several challenges that climate change poses for field crops. He also emphasizes potential adaptations to these challenges by addressing the options in biodiversity, agronomic practices and biofuels that could allow agriculture to adapt or mitigate climate change impacts on crop production. Uncertainties are discussed, including uncertainties in field experiments and in modeling, as well as climate predictions. The chapter illustrates potential changes that could maintain or increase productivity in an uncertain climate.

Mader and Gaughan (Chapter 3) summarize research on the effects of climate change on domestic livestock. The chapter explains the mechanisms by which increased climate stress affects animal metabolism, productivity and health. These mechanisms may cause domesticated livestock to face severe impacts due to climate change. The impact of climate change on animal production is quantified using indices of animal comfort and well-being. Alternatively, one could measure climate change impacts on livestock using economic measures such as net revenue (Mendelsohn and Dinar, 2009a). Specific strategies for minimizing the effects of adverse weather on livestock production are suggested. Finally, the chapter suggests that the carbon footprint of livestock be measured to capture the impact of livestock on greenhouse gas emissions.

Iglesias et al. (Chapter 4) provide a thorough review of the most common methods, models and tools currently applied to assess crop productivity and production changes due to climate change. This comparison is important because these tools and models vary in terms of their data requirements and the variables they take into consideration. In particular, the chapter focuses on those models used to assess impacts on crop production as well as those that estimate the economic impacts of climate change. Examples of the application of the models in diverse agricultural regions are given, from highly developed regions of Europe to poverty-stricken regions in Africa. The chapter also discusses several hurdles that researchers confront when modeling crop production; namely, changes in spatial scale, sources of uncertainty and variability.

Hayes et al. (Chapter 5) investigate the connections between climate change, drought and agricultural production. Some of the most obvious and damaging economic, environmental and social impacts from climate change/drought occur in the agricultural sector. These impacts include not only primary impacts on agricultural production, but also indirect and induced impacts on agribusinesses and on local and regional economies. The chapter describes these threats based on the current state of knowledge and presents examples that illustrate efforts to reduce the potential impacts of drought and climate change on agriculture.

ECONOMIC STUDIES OF CLIMATE IMPACTS ON AGRICULTURE

This part of the book examines economic studies of climate impacts on agriculture, utilizing various approaches, including mathematical programming, farm production models, intertemporal weather models and the Ricardian approach.

Peck and Adams (Chapter 6) use firm-level mathematical programming to discuss the underpinnings of mathematical programming techniques, and how they may be used to represent economic decision making in agriculture. The chapter then reviews the use of techniques involving climate change with a special emphasis on uncertainty, and discusses the limitations and the opportunities of these studies. Finally, the chapter provides guidance on the appropriate use of these techniques in addressing future climate change.

Deschenes and Greenstone (Chapter 7) demonstrate the use of panel-data models of interannual changes in weather across the USA to estimate the economic impacts of weather on agricultural production. The chapter presents the key theoretical and empirical issues in using panel-data methods for this purpose. Then it reviews and interprets recent literature based on panel data using data from the US Census of Agriculture.

Masseti and Mendelsohn (Chapter 8) demonstrate the use of repeated cross-sections to estimate Ricardian models. Ricardian models generally rely on data from a single year. By using multiple years of data, the authors show that a more robust measure can be obtained. However, in conducting such an analysis it is important to include critical control variables, accurate climate data, all relevant observations and the correct functional form. Using the repeat cross-sectional analysis on US data, the authors estimate the impact of climate change on US agriculture.

AGRICULTURAL IMPACTS ON THE ECONOMY

Because the agricultural sector is a significant part of the economy in many countries, what happens in this sector has wide-ranging effects. This part of the book explores macroeconomic models, trade and integrated assessment models as tools for explaining the role of agriculture in these larger issues.

Calzadilla et al. (Chapter 9) develop an economy-wide model to estimate how climate change impacts on agriculture affect the economy. The model incorporates international markets and other sectors as well as agriculture. The authors use IMPACT, a global partial equilibrium agricultural sector model combined with a water simulation model and GTAP-W, a global general equilibrium model including water resources. The methodology combines advantages of a partial equilibrium approach, considering detailed water and agriculture linkages, with a general equilibrium approach, which takes into account linkages between agriculture and non-agricultural sectors and includes a full treatment of factor markets.

Leimbach et al. (Chapter 10) discuss how agriculture is depicted in climate change integrated assessment models (IAMs). The IAMs are used to evaluate the interaction between mitigation and impacts. As such, agriculture is modeled as a source of greenhouse gases, a substitute energy source for fossil fuels as well as a damaged sector from climate change. The chapter discusses how carefully agriculture is modeled in each of the

major IAMs and then discusses the results of relying on biomass as a substitute for fossil fuels using the REMIND–MAGPIE–LPJmL.

The role of trade is explored by Reilly (Chapter 11). The starting point of the chapter is the observation that climate will have a range of effects across regions of the world. The global impact will depend upon how much trade is allowed from regions with more production to regions with less. The chapter uses a simple graphical analysis of the effects of trade on consumer and producer surplus to review basic economic trade results. Trade and agricultural impacts are discussed, given growing global incomes, changing food demands, multiple environmental impacts, competing demands for land, effects of carbon dioxide (CO₂) and tropospheric ozone and biofuels.

AGRICULTURAL MITIGATION

This part of the *Handbook* discusses the role that agriculture may play in greenhouse gas mitigation. Hochman et al. (Chapter 12) analyze the effects of increased investment in, as well as subsidization of, biofuels on the economy. The authors expect that future mandates requiring adoption of biofuels are likely to result in further substitution away from fossil fuels and a reduction in greenhouse gas emissions. However, the introduction of biofuels may contribute indirectly to greenhouse gas emissions through expansion of farming and resulting deforestation. The chapter compares the impact on social benefits from a carbon tax, a cap-and-trade system and renewable fuel standards, all of which are in the present policy discourse. In searching for policies to enhance adoption of biofuel and the resulting reduction in greenhouse gas emissions, the authors evaluate the effectiveness of less strict regulation of biotechnology that will allow increased agricultural productivity.

Larson et al. (Chapter 13) observe that while agriculture is one of the most vulnerable climate sensitive sectors, agricultural activities can act both as a carbon source, exacerbating greenhouse gas pollution, as well as a carbon sink, for agricultural soils possess great capacity to store CO₂. The chapter examines the use of JI (Joint Implementation) and CDM (Clean Development Mechanism) to encourage agricultural mitigation projects. The chapter contrasts the potential and the actual investments in this sector. It then explores the policy reasons for the resulting discrepancy between the actual outcome using JI and CDM and its potential.

ADAPTATION TO AGRICULTURAL IMPACTS

The final part of the *Handbook* explores the potential of adaptation as a response to climate change in agriculture. Sources of adaptation include research and development (R&D), improving the effectiveness of institutions, insurance, irrigation and crop and livestock switching. Aisabokhae et al. (Chapter 14) discuss the promise and challenges of using adaptation to address climate change in the agricultural sector. The chapter relies on a literature review, the results of the authors' own research and an econometric investigation of the implications of climate change for research returns. The chapter reviews data to assess the extent to which climate change damages can be mitigated by changing

crop varieties and shifting planting dates. A mathematical programming model of US agriculture is used to investigate the economic value of crop mix migration, varietal adaptation, livestock mix change, irrigation change and research investment.

Medellin-Azuara et al. (Chapter 15) develop a hydro-economic model to assess climate impacts and adaptation in Californian agriculture in the year 2050. The effect of larger populations and urbanization is taken into account. Warm-dry forms of climate change are likely to reduce surface water and could reduce agricultural production throughout California. The study explores the merits of reallocating water, technological change and alternative water sources as adaptations.

Fleischer and Kurukulasuriya (Chapter 16) examine the interaction of crop and irrigation technology choice as climate changes across agro-ecological zones. Using a cross-section of household-level data from Africa and Israel, the chapter examines the determinants of irrigation technology selection given particular crop choices. The results are used to project the implications of climate change and irrigation technologies on farm incomes. Israel and Africa reflect a technological and income spectrum when it comes to the role of technology and infrastructure.

Gollin (Chapter 17) discusses the prospects for adaptation via R&D. The chapter explores some of the emerging climate-linked challenges faced by breeders and draws on empirical evidence to suggest likely directions for crop and livestock research. The chapter also discusses the importance of continued management improvements and increased input.

Thornton et al. (Chapter 18) address adaptation to climate change in mixed crop-livestock farming systems. The chapter argues that crop-livestock systems serve as robust approaches for poor farmers to cope with climate variation. However, mixed crop-livestock farms tend to have low intensity and will face increasing pressure in the future from human population growth and competition for land and water. The chapter reviews what is known about the impacts of climate change on mixed systems, particularly in developing countries. It then discusses adaptation options at the level of the household, community and landscape that can help mixed crop-livestock farmers improve livelihoods and food security in the face of global change.

Garrido et al. (Chapter 19) examine insurance as an adaptation to climate variability in agriculture. The chapter begins by reviewing alternative modalities of agricultural insurance as they are found around the world. It then addresses the challenges that insurance faces as climate changes. Numerical examples are used to illustrate to what extent insurance can provide feasible adaptation strategies. The chapter also reviews the technical, institutional and financial requirements that are needed to promote agricultural insurance in developed and developing countries as an adaptation measure to climate change.

Seo (Chapter 20) models the choice of livestock species in Africa and Latin America as an adaptation to climate change. He relies on agro-ecological zones to extend a limited sample to all of Africa. The chapter applies a multinomial logit model to estimate the probability that farmers in each agro-ecological zone in Africa and Latin America select each type of livestock. The comparison between Africa and Latin America allows the author to verify whether or not farmers in both continents have similar behavior.

Saleth et al. (Chapter 21) provide an analytical framework to assess the effectiveness of institutions and infrastructure in encouraging adaptation of the agricultural sector to

climate change. The chapter applies a methodology that measures the critical linkages between the success of adaptation options and strategies, and the effectiveness of their underlying institutions and their performances. The chapter covers agricultural, rural, and water institutions. The methodology focuses on the individual and joint impact of these multiple institutions.

CONCLUSION

Finally, Mendelsohn and Dinar (Chapter 22) in the concluding chapter provide a summary of all the chapters. The conclusion examines the contributions of each chapter and brings out the common insights. It also identifies future research needs to understand the impacts of climate change on agriculture, how agricultural actors may adapt and what role agriculture may play in mitigation. The conclusion identifies the role of individuals and the role of institutions in finding effective solutions.

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PART I

AGRONOMIC STUDIES OF CLIMATE IMPACTS AND ADAPTATION

2 Climate change, carbon dioxide and global crop production: food security and uncertainty

Lewis H. Ziska

INTRODUCTION

As you read this, the global population will have surpassed the 7 billion mark (Table 2.1). At present growth rates, human populations will exceed 9 billion in the next few decades. As population expands, crop production must increase accordingly to maintain food security.

While globally there are over 250 000 plant species, only a very small fraction of them, primarily cereals, are suitable for human consumption. Indeed, approximately half of global caloric intake can be accounted for by only three cereals – corn, rice and wheat (Diamond, 1997). To understand how crop production has been so successful in supplying the food needs of 7 billion individuals, it is necessary to examine the ‘Green Revolution’.

A REVOLUTION IN FOOD SECURITY

In the postwar period of the late 1940s, there was widespread concern regarding famine. Cereals such as rice were not responding to additions of water and fertilizer; given these additional inputs, the plant became top-heavy and lodged (fell over), and the seed would rot, actually reducing yields.

The term ‘Green Revolution’ was first used by William Gaud, then administrator of the Agency for International Development (AID) in 1968 (Cassman, 1999). It was an acknowledgment of the work by Norman Borlaug, George Harrar and others in the development of new dwarf cereal varieties in the 1950s, and the global release of those varieties in the 1960s. These varieties were smaller in size and less top-heavy. They allocated more energy to grain production and less to vegetative matter. As a result, they responded well to inputs of water and fertilizer and did not lodge. Following their introduction, yields per hectare of rice, wheat and other cereals increased rapidly around

Table 2.1 Population milestones by billions

World population estimates milestones									
Population (billions)	1	2	3	4	5	6	7	8	9
Year	1804	1927	1960	1974	1987	1999	2011	2025	2040
Years elapsed		123	33	14	13	12	12	14	15

Source: Data from US Census Bureau, www.census.gov/ipc/www/idb.

the world (Harrar, 1970). Because of the importance of cereals as a source of calories, the rapid increase in their availability had profound revolutionary global impacts, particularly in Asia, where food-importing countries of the 1950s and 1960s became food exporters by the 1970s (Borlaug, 1983).

While no one disputes the impact of the Green Revolution, we are also dependent on its continued success. That is, to increase crop production for an expected population of 9 billion, large inputs of fertilizer and water will be required. These inputs, in turn, will be dependent on energy supply.

In addition to water and fertilizer, the Green Revolution depends on climate stability. Modern agriculture, particularly in developed countries, occurs on a vast land scale, usually in the hundreds, and often thousands, of hectares. Mechanization is needed to farm at this level; usually only one or two crop varieties are planted to maintain consistency of fertilizer rates, time of harvest and so on as a means to lower the economic costs of farm operations.

CO₂, CLIMATE AND CROP PRODUCTION

Given the additional need for food and energy to meet the demands of an expanding population, and our current reliance on fossil fuels to address those needs, it is reasonable to conclude that human-derived sources of atmospheric carbon dioxide (CO₂) will continue. At present rates of generation, CO₂ is expected to exceed 600 parts per million (ppm) globally by the end of the current century (IPCC, 2007). Indeed, in spite of the scientific consensus reflected in the latest Intergovernmental Panel on Climate Change (IPCC, 2007) projections, actual CO₂ increases appear to be exceeding even the most dire, 'business-as-usual' IPCC scenarios on an annual basis (Figure 2.1 – see p. 246).

A direct by-product of fossil fuel consumption (and, to a lesser extent, deforestation) is the accumulation of atmospheric trace gases (e.g. CO₂). Many of these trace gases absorb energy in the infrared portion of the spectrum, and, as such, are considered to be global warming or greenhouse gases. In addition to CO₂ (the principal greenhouse gas), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbons (CFCs) are also accumulating in the atmosphere as a result of human activities (IPCC, 2007).

Recent and projected increases in these gases will have two general consequences for global crop production. The first of these is related to climate stability. The rise of CO₂ and associated greenhouse gases could lead to a 3–12 °C increase in global surface temperatures, with consequences for precipitation frequency and amounts (IPCC, 2007). Moreover, the differential extent to which the increase in CO₂ and other anthropogenic greenhouse gases alters surface temperature and water availability is likely to vary temporally and geographically (Cushman, 1999), with subsequent increases in climatic extremes.

The second consequence is related to the role CO₂ plays in photosynthesis and growth. Plants evolved at a time of high atmospheric CO₂ (4–5 times present values), but concentrations appear to have declined to relatively low values during the last 25–30 million years (Bowes, 1996). The values have been low for long enough that evolution has selected for a small percentage of plants, principally tropical grasses, that have maximum photosynthetic rates even at the current low CO₂ concentrations. However, these grasses

(termed C_4 plants) comprise only about 3–4 per cent of all known plant species, and the bulk (95 per cent) of the 250 000 or more plant species (termed C_3 plants) lack optimal levels of CO_2 . For these plants, the recent rise and projected increase in atmospheric CO_2 represents an upsurge of an essential resource. To that end there are, literally, hundreds of studies showing that both recent and projected increases in atmospheric CO_2 can significantly stimulate growth, development and reproduction in a wide variety of C_3 plants (see Kimball, 1983; Kimball et al., 1993; Poorter and Navas, 2003 for reviews examining the response to future CO_2 concentrations; see Sage, 1995 for a review of the response to recent CO_2 increases).

CLIMATE, CO_2 AND CROP PRODUCTION: DIRECT EFFECTS

Overall, the global population of ~7 billion is possible only because of large external inputs of water and fertilizer as well as climate stability. How then are physical (abiotic) aspects of global climate likely to disrupt crop production?

Water

The agricultural sector that is likely to be most impacted by climate change is irrigation. One ton of cereal grain requires between 500 to 1000 tons of water to produce. At present, about 67 per cent of the current global water withdrawal, and 87 per cent of the consumptive water use (withdrawal minus return flow) is for irrigation purposes (Shiklomanov, 2000). Although irrigated agricultural land comprises less than one-fifth of the total cropped area, it produces about two-fifths of the world's food (Döll, 2002). For example, rice is a subsistence crop that supplies the majority of calories for 1.5 billion people. Although the area planted with rice is roughly equivalent between irrigated and non-irrigated fields, it is the irrigated rice that accounts for 75 per cent of total rice production (Bouman et al., 2007). If we are to feed an additional 2 billion people in the next 30 years, irrigated agriculture will have to expand. Yet, at present, it is unclear how these demands will be met in the context of water availability and climate change.

In a warmer world, with the possibility of greater climatic extremes (e.g. drought, flooding), uncertainty of water supply in agriculture is also likely to rise, aside from any change in population. Long-term average irrigation requirements indicate that approximately two-thirds of the area currently under irrigation globally will experience greater water requirements by 2070 (Döll, 2002). Agriculture could shift poleward to regions where climate change will decrease per hectare in irrigation demand (e.g. USA to Canada); however, this is not always practical from a geopolitical or edaphic point of view (e.g. India to Nepal).

As demand for water shifts, climate change is also likely to negatively impact supply. Much of the surface runoff used in irrigation is derived from snow and ice melt from mountain sources. These sources may be particularly vulnerable to warmer and drier conditions (IPCC, 2007; Immerzeel et al., 2010). For example, Hayhoe et al. (2004) evaluated general trends for agriculture in California, which leads the USA in agricultural production and is highly dependent on snowpack in the Sierra Nevada for

irrigation water. This analysis indicated that climate-induced demand was likely to be accompanied by a significant reduction in snowpack and a shift to earlier runoff. Such shifts are already apparent not only in California, but in historical records of the western USA (Kerr, 2007; Barnett et al., 2008). A similar response may have already occurred in Australia's Murray–Darling River complex (CSIRO, 2008). Groundwater supplies from aquifers are also likely to be affected in arid regions, due in part to declining water tables (overdrafts) and increasing pumping costs. At present, regions supplied by the Ogallala aquifer (including parts of Nebraska, Oklahoma, Texas, Colorado and New Mexico) may be taken out of irrigation due to excessive overdrafts (McGuire, 2007).

In addition to climate change, assessments of water supply and demand are complicated by other factors. For example, water demands will increase not only because of agriculture, but also because of expanding human populations and economic development (Vorosmarty et al., 2000). Competition between urban areas and agriculture over existing supplies are likely to be particularly exacerbated in arid regions (e.g. Australia, American West) with projections of increased desertification (IPCC, 2007).

Overall, the warming aspect of anthropogenic climate change dominates much of the environmental focus. Yet quantifying the impact of climate change on irrigation and crop production in the context of existing competition for available water resources remains elusive, with only a handful of global assessments. In addition, evaluation of the other extreme, flooding, is rarely considered in global climate models regarding agricultural productivity.

Fertilizer

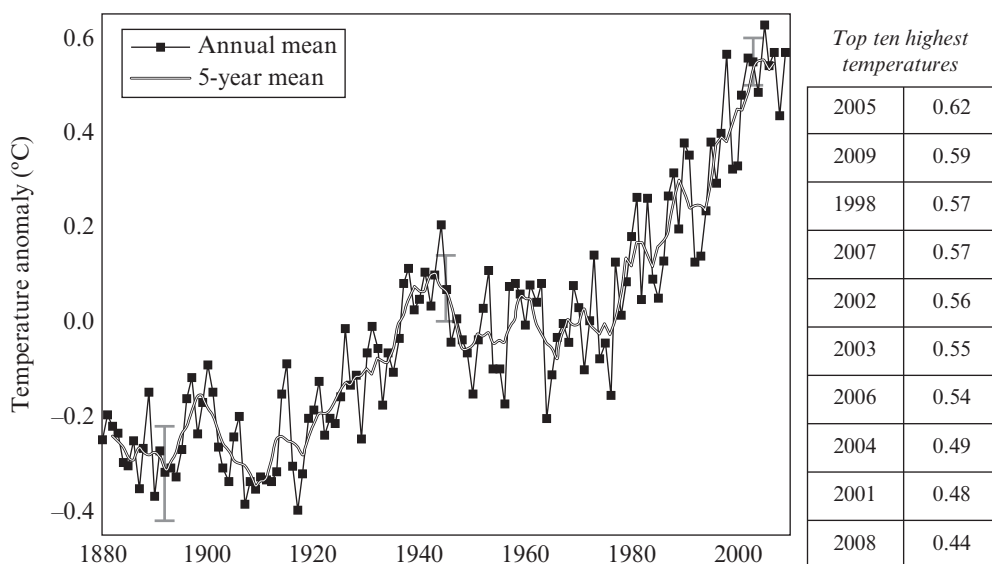
When people think of a farm they often picture a sharing of resources between animals and plants (e.g. manure for corn, corn for cows). However, as a result of the Green Revolution, the scope of modern agriculture has expanded so that synthetic fertilizers must be used in order to maintain maximum yield of cereals. These fertilizers, particularly nitrogen, are heavily dependent on fossil fuels.

About half of the global input of nitrogen fertilizer applied each year in agriculture is derived from the Haber–Bosch process. This process uses high heat and pressure to combine hydrogen (usually obtained from methane) with atmospheric nitrogen to create ammonia, ammonia nitrate and urea. However, this reaction can only occur at high temperatures and pressures, and is very energy intensive, using approximately 1 per cent of the total available global energy in a given year.

The link between energy, fertilizer production and crop production is critical because the Haber process is used to produce about 500 million tons of nitrogen fertilizer annually. Any decrease in the availability of energy, particularly from a decline in fossil fuel production, could cause a significant interruption or increase in the cost of fertilizer. It is no coincidence, for example, that the record high prices of fossil fuels in 2008 were associated with record cereal prices of corn, wheat and rice for that year (NASS, 2010).

Temperature

The Green Revolution varieties came into use during a time of relative temperature stability during the mid twentieth century (Figure 2.2). Recent evaluations of temperature



Note: The mid-twentieth century was a time of stable climate.

Source: National Oceanic Atmosphere Administration (NOAA).

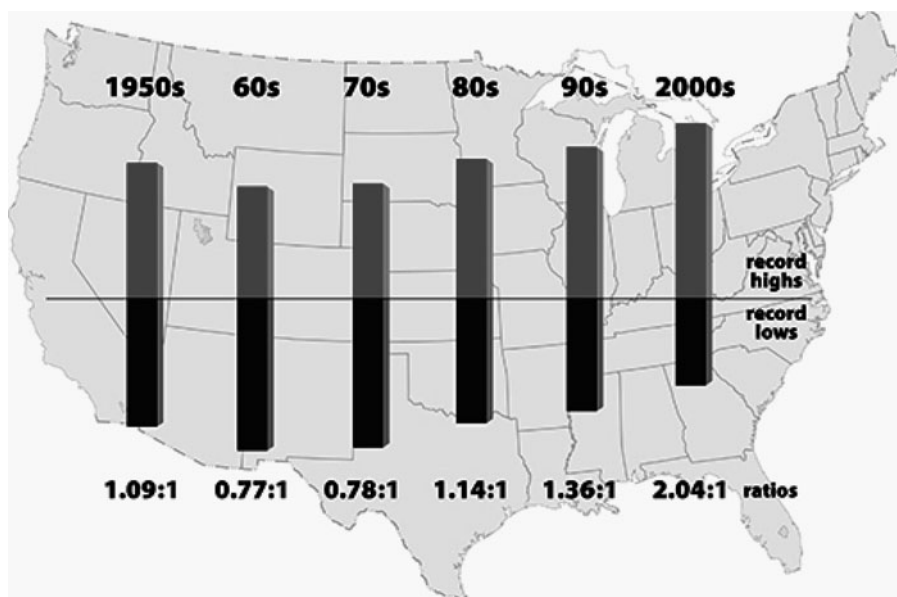
Figure 2.2 Land-ocean temperature index

Table 2.2 Optimal temperatures for vegetative and reproductive development of selected crop species in the USA (note the critical temperature at which infertility occurs)

Crop	Opt. temp. vegetative(°C)	Opt. temp. flowering(°C)	Failure temp. flowering(°C)
Maize	28–35	18–22	35
Soybean	25–37	22–24	39
Wheat	20–30	15	34
Rice	28–35	23–26	36
Sorghum	26–34	25	35
Cotton	34	25–26	35
Peanut	31–35	20–26	39

thresholds demonstrate that pollen sterility and seed set are much more temperature sensitive than vegetative growth for many key crop species (Table 2.2). Temperature sensitivity for economically important crops indicated a non-linear response of yields to temperature, with a significant decline in yields even with small temperature increases above a physiological threshold (Hatfield et al., 2008). The sudden decline in yield with temperature appears to be related to pollen infertility during flowering (Hatfield et al., 2008).

This non-linear temperature response was evaluated for corn, soybean and cotton



Note: Each bar shows the proportion of record highs (light grey) to record lows (dark grey) for each decade. In the last 30 years record highs have increasingly predominated, with the ratio now about 2:1 for the 48 states as a whole.

Source: Data from the University Center for Atmospheric Research (UCAR).

Figure 2.3 Ratios of record daily highs to record daily lows as determined from ~ 1800 weather stations in 48 contiguous US states, January 1950–September 2009

(crops with the largest economic value in the USA) by Schlenker and Roberts (2009). They found that yields of the three increased up to temperatures of 29, 30 and 32 °C, respectively, but that yields declined precipitously above this temperature (Schlenker and Roberts, 2009). They projected that if current growing regions remained fixed, average yields in the USA would decrease by 30–46 per cent and 63–82 per cent for the slowest and most rapidly warming climate change scenarios (IPCC, 2007).

Climatic Extremes

As described previously, large-scale farming is dependent on highly specialized, uniform cropping systems. However, because of the physiological limits inherent in a single variety, the occurrence of an extreme weather event can significantly reduce yields. As reported by the US Climate Change Science Program (Backlund et al., 2008), a typical Midwestern drought can reduce corn yields in the USA by 30 per cent. Yet, because surface temperatures are warming at different rates, the projections are for a greater prevalence of extreme weather (IPCC, 2007). As one-in-hundred-year events become one-in-ten-year events, the occurrence of weather extremes, particularly in an interlinked food market, poses great risks for global food security (Figure 2.3). In 2010, for example, extreme heat and drought devastated Russia's wheat crop; Mexico and the southwestern

USA also experienced the worst drought in 50 years. Conversely, one-fifth of Pakistan was destroyed by flooding, while Canadian harvests were damaged by excessive rains during cereal planting. The net result of all of these events (sometimes referred to as global weirding) has been an unprecedented surge in cereal prices and food insecurity. If, at present, the global market relies on the USA to supply a significant portion of the demand for global grains, how can growers in North America cope with a future in which extreme weather events are routine?

CLIMATE, CO₂ AND CROP PRODUCTION: BIOLOGICAL EFFECTS

The last section presented some of the physical or abiotic inputs likely to directly impact crop productivity. However, it is also clear that at the biological level a number of other indirect changes are likely to disrupt agricultural outputs.

Agro-ecosystems

It is easy to forget when looking at a farmer's field that more than one species is being grown there. Agricultural fields, while uniform with respect to the crop, are also home to weeds, insects, diseases, and so on. It is this amalgam of different organisms that is being referred to here as an agro-ecosystem.

As with any environmental perturbation, species are likely to respond differentially with climate change. It is this differential response that may have biological consequences for crop production. For example, weeds, which impose the largest single limitation on crop yields (Oerke, 2006), are also likely to respond to climate change and increasing CO₂ concentrations. An overview of crop and weed competitive studies indicates that weeds could limit crop yields to a greater extent with rising levels of CO₂ (Table 2.3). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems. Greater diversity may be advantageous in a rapidly changing climate (Ziska and Runion, 2007).

The role of climate change and/or rising CO₂ in disease and insect biology, as well as the consequences for crop production, are more difficult to quantify. Warmer, wetter conditions can facilitate the spread of diseases or increase insect fecundity (Scherin and Coakley, 2003; Ziska and Runion, 2007). Increasing atmospheric CO₂ may also affect plant function and hence indirectly affect insects and disease. However, the interactions of crops, diseases and insects with respect to agricultural productivity are complex. For example, both beneficial and harmful insects are likely to be affected by climate or substantive changes in the plant host (Patterson et al., 1999). Similarly, a shift in climate could bring in new diseases but also shift the optimal conditions for existing pathogens (Fuhrer, 2003).

Management of pests, particularly weeds, is also likely to be affected. For many industrialized countries, chemical application of herbicides allows for cheap, effective weed control in crop production. In fact, a single herbicide, glyphosate (commercially sold as 'Round-Up'), is so effective in controlling weeds that more than three-quarters of the US soybean crop and over one-third of the US corn crop have been genetically modified to be glyphosate resistant (Gaskell et al., 1999). However, there are several studies

Table 2.3 *Summary of studies examining whether weed or crops grown in competition were 'favored' as a function of elevated CO₂*

Crop	Weed	Increasing CO ₂ favored	Environment	Reference
A. C ₄ crops / C ₄ weeds				
Sorghum	<i>Amaranthus retroflexus</i>	Weed	Field	Ziska (2003)
B. C ₄ crops / C ₃ weeds				
Sorghum	<i>Xanthium strumarium</i>	Weed	Glasshouse	Ziska (2001)
Sorghum	<i>Albutilon theophrasti</i>	Weed	Field	Ziska (2003)
C. C ₃ crops / C ₃ weeds				
Soybean	<i>Chenopodium album</i>	Weed	Field	Ziska (2000)
Soybean	<i>Canada thistle</i>	Weed	Field	Ziska (2010)
D. C ₃ crops / C ₄ weeds				
Fescue	<i>Sorghum halapense</i>	Crop	Glasshouse	Carter and Peterson (1983)
Soybean	<i>Sorghum halapense</i>	Crop	Chamber	Patterson et al. 1984
Rice	<i>Echinochloa glabrescens</i>	Crop	Glasshouse	Alberto et al. (1996)
Soybean	<i>A. retroflexus</i>	Crop	Field	Ziska (2000)

Note: 'Favored' indicates whether elevated CO₂ produced significantly more crop or weed biomass.

indicating a decline in herbicide efficacy as a function of increasing atmospheric CO₂ and/or temperature (Archambeault, 2007; Ziska et al., 1999; Ziska and Teasdale, 2000).

Globally, there are several additional means of weed management, most notably mechanical, biological and cultural. Although data are scarce, there are cogent reasons for anticipating potential changes in these management strategies in response to changing climate and CO₂ concentrations. For example, tillage (physical cultivation to remove weeds in the field) could be affected by precipitation extremes that could limit field operations. Rising CO₂ levels could also increase root or rhizome growth of perennial weeds with subsequent effects on increasing asexual reproduction (Rogers et al., 1994; Ziska et al., 2004); tillage, in turn, could exacerbate asexual production by spreading additional roots or rhizomes in the field. The efficacy of weed biocontrol agents (e.g. insects) is dependent on synchrony between various aspects of the plant community. As climate and/or CO₂ levels change, differential responses among host and biocontrol agents could occur. Cultural weed management reflects farm strategies that can control weeds, such as flooding. Yet it is also clear that water supply and demand are likely to be impacted by climate change too.

Nutrition

Researchers are obviously concerned regarding the impact of CO₂ and climate change on crop production and food security. However, it is equally important to consider the quality or nutritional aspects of the food supply.

A study of major food crops including barley, wheat, soybean and potato indicated a significant decline (~10–15 per cent) in protein content if atmospheric CO₂ increases

to between 540 to 960 ppm (Taub et al., 2007), a range anticipated by the end of this century (IPCC, 2007). This is due, at least in part, to the fact that as CO₂ increases, photosynthesis requires less nitrogen (i.e. nitrogen use efficiency, the ratio of C to N, typically increases). In addition to this dilution of protein levels, rising CO₂ may also reduce water flow through the crop plant due to its physiological effect of closing stomata. As a result, uptake of key micro and macro nutrients from the soil (e.g. iron, zinc, manganese) may also be negatively impacted with respect to human health (Loladze, 2002).

The UN Food and Agriculture Organization estimates that more than 1 billion people worldwide are malnourished (FAO, 2009). Malnutrition generally results from a lack of either protein, which is needed for muscle development and maintenance, or micronutrients such as iodine, vitamin A or iron, which boost immunity and healthy development. For many populations in the developing world, meat is scarce and plants provide the primary source of both protein and micronutrients. If, as we expect, rising CO₂ levels reduce the concentration or affect the nutritional quality of crops, then it is possible that impoverished areas of the world already threatened by shortages in food supply may face an additional burden of 'hidden hunger'.

Food Safety

Disease outbreaks and sickness due to tainted food remain a consumer priority. Climate change will bring higher temperatures and additional climatic extremes, particularly more extreme precipitation.

Evidence of the impact of climate change on the transmission of food and waterborne diseases is a function of a number of sources, such as the seasonality of foodborne and diarrheal disease, changes in disease patterns that occur as a consequence of temperature, and associations between increased incidence of food and waterborne illness and severe weather events (Hall et al., 2002; Rose et al., 2001).

Cholera may serve as a model for understanding the interaction of climate change and the transmission of a foodborne disease. *Vibrio cholerae* is the causative agent of this disease, which gives rise to substantial morbidity and mortality, particularly in the developing world. Peaks of disease are seasonal and associated with higher water temperature. While cholera is predominantly a waterborne disease, transmission can occur through the use of contaminated water for food preparation, shellfish consumption or through irrigation contamination.

Climate constrains the range of infectious diseases, while weather affects the timing and intensity of outbreaks (Epstein, 2001). Two early manifestations of climate change, particularly global warming, could be expansion in the geographic range and seasonality of disease, and the emergence of outbreaks occurring as a consequence of extreme weather events (Epstein, 2001).

Taken together, changes in both ambient temperature and humidity appear to play a role in foodborne disease transmission that is independent of population behavior and susceptibility (FAO, 2008). It is likely that some of the first detectable impacts of global climate change on food safety will be seen as longer summertime peaks of foodborne disease and/or increased geographic range (Watson and McMichael, 2001).

CLIMATE AND FOOD SECURITY: ADAPTATION AND MITIGATION

There are, then, a number of means by which climate change is likely to adversely affect food security. In the context of these vulnerabilities, what are (some) potential solutions that can safeguard crop production?

Diversity and Polyculture

Agronomists recognize that production sustainability is, in large part, related to climate stability. The middle of the twentieth century, a time when most of the Green Revolution cereals were being developed, was in fact a time of stable temperatures and rainfall (Swanson et al., 2009). Unfortunately, even without anthropogenic climate change there is some evidence that the twentieth-century climate may be an anomaly (IPCC, 2007). Given that crop production is dependent on highly specialized, genetically uniform cropping systems, it will always be susceptible to climate perturbation.

Yet plants, including many crop species, are not genetically uniform in nature. Because of climate variability there are, even within a species, a large number of biotypes that are adapted to a wide range of abiotic (e.g. temperature, water) conditions. As climate changes, there is therefore a need to diversify crop production to account for climatic extremes in order to maintain crop production and sustainability.

At the farm level such diversification can take the form of polyculture. Polyculture is the production of several species (animal and plant) concurrently, where outputs and inputs for each species are in balance. For example, crop and animal diversity can be maintained when fertilizer from animal waste is used to improve soil health, and soil health, in turn, provides additional crops to feed the animals. Maintaining biological diversity helps to ensure that any one crop or animal line is not eliminated due to climatic extremes. Traditionally, this approach has been very successful (e.g. Pimental et al., 2005). However, as farms have become larger and costs have escalated, there has been a trend to streamline crop and animal production. Such streamlining includes the use of concentrated animal feeding operations, or CAFOs. Unfortunately, in this instance the waste generated by such large feedlots is water soluble, and has contributed to the recent appearance of large 'dead zones' in the Gulf of Mexico. While the use of such streamlined techniques may be cost saving over shorter durations, long-term environmental costs may make such an approach unsustainable (Roberts, 2008). Rather, diversification of farm operations and polyculture establishment may be critical to sustainable crop and livestock production.

Exploitation of Genetic Resources

Preservation of crop diversity is also necessary because each crop variety represents a different response to a range of abiotic (e.g. temperature, water) and biotic (e.g. insects, diseases) stresses. Given sufficient time, reliance on a single variety will result in yield loss due to exposure to pathogens, weeds or environmental limitations. If diversity provides sustainability in an uncertain climate, can it also be exploited as a means to increase productivity?

Recall that CO₂, in addition to being a greenhouse gas, is also a resource for plant growth as it provides carbon for photosynthesis. Other resources include nutrients, water and sunlight. As we would not expect all plants to respond in the same way to an increase in sunlight, water or nutrients, we would not expect all plants to respond in the same way to CO₂. What then are the best, most responsive, crop varieties? How much variation in CO₂ exists within a single crop? Can these variations be exploited not only to convert additional CO₂ into seed yield but to also identify more temperature- or drought-tolerant lines? Initial data indicate that there is significant intraspecific variation among both cultivated and wild lines of cereal species that could be used to maintain or even increase crop yields with CO₂ and/or climate (Edwards and Newton, 2007; Ziska, 2008).

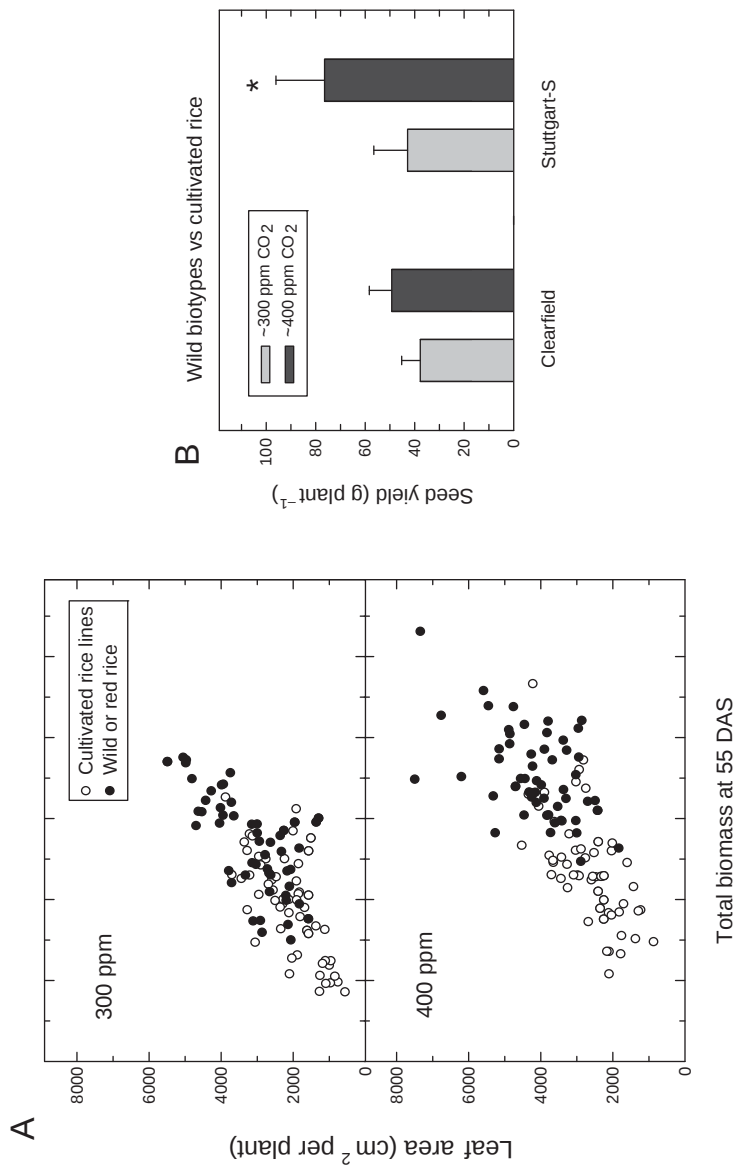
With respect to crop production, inclusion of additional varieties of the same crop gives farmers a tool to adapt to changing conditions. For example, wild relatives of potato were used to derive new lines to combat the plague of *Phytophthora infestans* that infected the potato fields of Ireland and caused the deaths of over a million people in the mid-nineteenth century. Many wild relatives are closely related to cultivated crops (e.g. wild oats and oats, sorghum and shattercane) and are considered to be agronomic weeds. Yet could the ability of these weeds to produce seeds in a wide range of adverse conditions be utilized as a simple means to adapt cultivated crop lines to climate change?

There is sufficient variability among wild biotypes that incorporation of a desired phenotypic or genotypic trait into cultivated lines as a form of hybridization is an attractive possibility. For example, as temperatures increase, crop reproduction often fails before vegetative growth due to greater temperature sensitivity of pollen (Hatfield et al., 2008). This is true of many cultivated rice lines. In contrast, there are wild rice lines (*Oryza* spp.) that may flower earlier in the morning or at night and therefore escape potential reproductive stress (Prasad et al., 2006). Initial results of Ziska and McClung (2008) indicate a greater physiological plasticity and genetic diversity among wild rice biotypes relative to cultivated rice varieties, particularly in converting additional CO₂ to growth and/or seed yield (Figure 2.4). This greater variation in rice and other cereals may also provide a unique genetic resource that could be incorporated into cereal cultivars as a means to increase their adaptability to climatic change or, alternatively, increase their ability to exploit additional CO₂ for enhanced seed yield.

Infrastructure/technology

While technical innovations are always an adaptive strategy, we should avoid expectations that emphasize a magic, one-size-fits-all, future solution. Rather, there are a number of opportunities to increase the efficacy of current tools. Such opportunities include: increasing the infrastructure needed for water availability (e.g. small dams) at the regional level, including more efficient delivery of water (e.g. drip irrigation); and precise application of fertilizer inputs (e.g. fertigation).

An example of the last can be related to corn production. Corn is fertilizer intensive, and determining the proper nitrogen (N) rate is important to achieve maximum corn yields. If fossil fuel costs are low, producers will often over-apply nitrogen to ensure a high yield. However, rising fuel costs and groundwater concerns have led growers to



Note: At the lower, pre-industrial concentration, responses among lines are similar, but as CO_2 has increased, wild lines have shown a stronger growth response. During the twentieth century the wild rice line exhibits a stronger response to CO_2 increases.

Figure 2.4 (A) Leaf area as a function of total biomass for six cultivated (open circles) and six wild (closed circles) lines of rice at 300 and 400 ppm CO_2 . (B) Seed yield for one cultivated (Clearfield) and one wild (Stuttgart red) rice line at 300 and 400 ppm CO_2

emphasize efficiency and profitability of nitrogen applications. One means to increase nitrogen use efficiency (NUE, the ratio of yield to nitrogen applied) is to use the crop itself as a means to determine if adequate nitrogen is being applied. Quantification of nitrogen within the corn plant offers an approach to determine crop nitrogen status and manage nitrogen application more effectively.

How can nitrogen status be quantified? A number of sensing tools are available, including the Minolta SPAD chlorophyll meter (CM). This meter is a handheld instrument that measures the greenness of corn leaves. The relationship between leaf greenness and nitrogen availability is well documented (Varvel et al., 1997). Corn plants will reach maximum greenness with sufficient nitrogen. When nitrogen is stressed, the plant will be less green. By quantifying the degree of 'greenness', application of nitrogen is directly related to the plant's need for it. As such, the overall efficiency of fertilizer input (and the resulting economic and fossil fuel savings) can be increased.

However, not all farmers can afford the latest electronic equipment. There may be other, cheaper means to increase resource efficiency at the farm level. For example, one under-utilized technology is that of cellphones. At present, almost two-thirds of the global population has access to such a device, and specific apps related to pest identification or nitrogen application, planting times, weather information would be invaluable, particularly for farmers in developing countries.

Overall, these examples (and others) offer strategic technological approaches to maximize application efficiency, minimize economic costs and maintain crop productivity with climate extremes and limited resources.

Biofuels

Although future methodologies are anticipated with respect to cellulosic fermentation and ethanol production, at present most of the ethanol needs of the USA are being met by the conversion of carbohydrate in corn (starch) to ethanol (Farrell et al., 2006). In 2006, approximately 20 per cent of US corn production was diverted to ethanol; by 2010, this had risen to 34 per cent, or 50 billion liters) (RFA, 2010). Since corn is one of the three principal cereals (corn, wheat and rice) that supply 50 per cent of the world's calories, there is increasing concern that greater diversion of corn feedstocks to meet ethanol demand may contribute to rising food prices and global hunger (Msangi et al., 2007).

Overall, biofuels should be seen as a complement and not a competitor in food production, particularly for cereals such as corn. In this regard, alternative sources of biofuel, particularly those that utilize marginal lands and require little external input (e.g. pesticides, irrigation), would be desired until cellulosic or other forms of biofuel production are widespread. For example, a recent evaluation of sweet potato (*Ipomoea batatas*) and cassava (*Manihot esculentum*) (Ziska et al., 2009) at locations near Auburn, Alabama and Beltsville, Maryland demonstrated that these crops, which require very low external inputs of fertilizer and pesticides, could yield significantly more ethanol than corn (Table 2.4). As such, these marginal crops could be used to replace or offset corn as a biofuel source.

Some consideration should also be given to existing non-crop sources as biofuels. Potential non-crop sources of ethanol include a number of potential weed species such as oriental grasses (*Miscanthus*), Russian thistle (*Salsola kali*), castor bean (*Ricinus*

Table 2.4 *Estimated ethanol production from potential bioethanol crop*

Crop	Ethanol (l ha ⁻¹)
Cassava ^A	6717
Cassava ^M	2746
Corn ^A	3797
Corn ^M	3399
Corn ^{US}	3880
Potato ^{US}	4884
Sugarbeet ^{US}	5891
Sugarcane ^{US}	6195
Sweet potato ^A	8141
Sweet potato ^M	8839
Sweet potato ^{US}	2608

Notes and sources:

^A This study (Alabama). ^MThis study (Maryland). ^{US}Based on average US yield per hectare.

Average yields were obtained from www.nass.usda.gov/QuickStats/indexbysubject.jsp for 2007. Data are liters per hectare. Conversion factors are from Johnston et al. (2009), Table 2. Data are from Ziska et al. (2009).

communis) and mesquite (*Prosopis* spp.). Because of the invasive nature of these weed species, widespread planting would have to be carefully regulated. However, some weed species already persist in such large geographic areas that use of existing populations as biofuel could both eliminate the weed and generate energy.

One such example may be kudzu (*Pueraria lobata*). Kudzu currently infests 3 million hectares in the USA and is increasing its areal coverage by over 50 000 hectares per year (Forseth and Innis, 2004). Kudzu costs the US economy some \$500 million per year in the form of lost crop and forest productivity, control costs and property damage (Blaustein, 2001). The success of kudzu is due in part to its production of large storage roots. These are rich in starch and other carbohydrates and can exceed 10 cm in diameter and extend over 2 m in length, with weights up to 180 kg (Miller and Edwards, 1983; Blaustein, 2001). To determine the potential of kudzu as a biofuel, Sage et al. (2009) examined biomass and carbohydrate contents of kudzu. Based on the yield data, they estimated that wild kudzu stands in Alabama and Georgia could produce 5 to 10 metric tons of carbohydrate per hectare, which would rival carbohydrate production from corn and sugarcane fields, but without the costs associated with planting, fertilizer and pesticides. Overall, kudzu has the potential to economically supplement existing plant sources of bioethanol, which could be of local significance to the rural economy of the southeastern USA. Clearly, regulatory issues would have to be resolved, particularly if kudzu is to become a renewable resource. However, kudzu provides an example of how some non-crop plants could be utilized as energy sources.

UNCERTAINTY AND CRITICAL NEEDS

Modern agriculture is highly dependent on the model of the Green Revolution characterized by the availability of cheap energy and plentiful water in the context of a stable

climate to maintain maximum cereal production. Yet it is also clear that all aspects of the Green Revolution model are, in fact, vulnerable to global climate change and fossil fuel use. While there are strategies available that can help crop production adapt to or mitigate the effects of a changing climate, a number of uncertainties and critical research needs remain unaddressed.

Experimental Uncertainties

An accurate evaluation of crop production for future projected climate scenarios requires scientists to attempt to simulate those scenarios under controlled conditions. Given the complexity of simultaneous environmental changes, such an appraisal using a traditional reductionist approach is difficult. Different simulation methodologies have been implemented over the years, but for many crop species the focus has been on growth response to CO₂ *per se* (Kimball 1983; Kimball et al., 1993). However, many of the crucial interactions of CO₂ and other factors (e.g. temperature, drought, pests, diseases etc.) have not been evaluated. Overall, methodologies used to ascertain plant responses to CO₂ have both positive and negative attributes; consequently, data obtained from a given experiment should not be judged superior based solely on methodology (Long et al., 2006). For example, environmental growth chambers (EGCs) are useful in evaluating the impact of pre-ambient CO₂ concentrations on whole plant development, but an EGC environment will differ significantly from *in situ* conditions. Conversely, free air CO₂ enrichment (FACE) allows assessment of plant communities, but rapidly fluctuating CO₂ concentrations within elevated FACE rings may underestimate the fertilization effect of enriched CO₂ on plant growth (Holtum and Winter, 2003).

In general, the cost and complexity of methodologies increase with spatial and temporal extremes. As a consequence, most of what is known concerning crop production at the field level may emphasize the response to CO₂, and may not consider other biotic (e.g. pests) or abiotic (e.g. temperature) interactions. Those methodologies that do allow an assessment of concurrent environmental parameters likely to occur with anthropogenic climate change (e.g. temperature and CO₂, CO₂ and drought) may be based on a smaller assessment within growth chambers or greenhouses. This does not mean that such assessments are inaccurate (e.g. Ziska and Bunce, 2007), but they usually reflect the level of whole plant response. Other levels of biological organization, both very large (e.g. ecosystem) and very small (e.g. genetic regulation), have not been adequately addressed.

Model Uncertainties

Overall, given the complexity and rapidity of environmental change, integration of abiotic and biotic uncertainties regarding crop production and food security cannot be addressed entirely through experimentation, but must include a crop modeling assessment (e.g. Matthews et al., 1995 for rice). Such models serve to integrate and synthesize existing information regarding CO₂/climate impacts and to project this information for a given region or environment. As such, modeling efforts are useful as potential projections of global consequences.

However, given the large adjustment in scale, uncertainties in crop yields at the experimental level are magnified considerably in regional or global assessments. For example, early projections of the effects of climate on rice yields assumed that rising CO₂ and temperature acted independently (i.e. the response to CO₂ did not change with temperature) (Kropff et al., 1994). Yet, since that initial assessment, it is clear that elevated CO₂ may exacerbate the negative effects of temperature, particularly on pollen sterility (Kim et al., 1996; Matsui et al., 1997). It is the incorporation of these experimental findings, whether for drought or flooding, cultivar selection or pest damage, that remains a key uncertainty in addressing vulnerabilities of crop production to global change. Understanding these uncertainties can be critical in developing robust models. For example, the role of temperature and climate change in the spread of invasive insects (e.g. pine bark beetle) and subsequent destruction of forests was not foreseen, but is now widely acknowledged (e.g. Kurz et al., 2008), yet an analogous modeling analysis of the vulnerability of agricultural productivity in North America to rising temperature and invasive insects has not, to date, been conducted. Indeed, many published assessments of the vulnerability of a given crop to climate change may be based on a handful of CO₂ experiments with no information on pests, diseases, intraspecies variability and so on (e.g. Ziska, 2008).

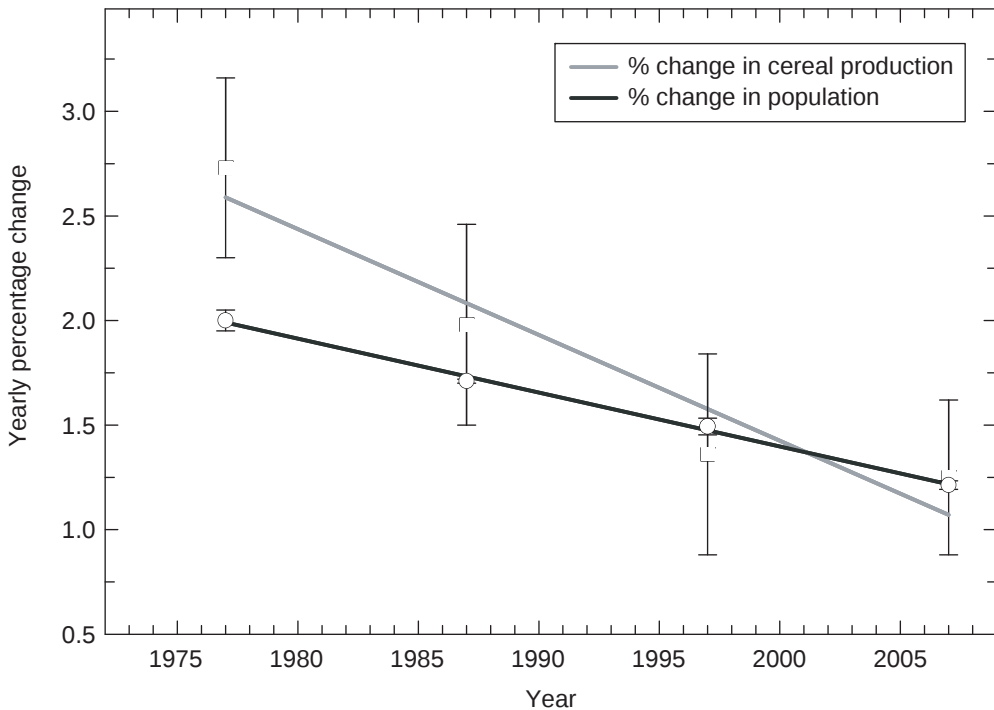
Climate Projection Uncertainties

For the twenty-first century, crop production and food security are no longer regional issues. The ability to grow and deliver highly specialized cereals, fruits, vegetables etc. is a global enterprise. As such, even regional perturbations in climate can be disruptive to the production and distribution of the global food supply.

It is unreasonable to assume that the mild conditions of the mid twentieth century will continue indefinitely, given the complexity of the weather–climate system. Clearly, anthropogenic change has the ability to push components of the system past a critical state in a different mode of operation (e.g. ‘tipping point’), one with large-scale implications for human and ecological systems. Some examples include the potential collapse of the Atlantic thermohaline circulation (THC), dieback of the Amazon rainforest and decay of the Greenland ice sheet, *inter alia* (Lenton et al., 2008).

What are the tipping points for crop production? A production analysis of the eight most widely grown cereals shows that the increase in cereal production (either as total cereal output or as the percentage of direct human consumption) relative to the percentage population growth has declined since the 1960s (Figure 2.5). These data indicate that the growth rate of cereal production probably fell below the population growth rate sometime at the beginning of the twenty-first century, signaling the end of the Green Revolution.

If crop production is, in fact, at its own tipping point regarding supply and demand, how is this likely to increase the vulnerability of food supply to climatic change? Will such vulnerability be evident if a critical temperature threshold for anthesis is reached (e.g. Table 2.2), and the resulting increase in sterility results in a sudden, irrevocable loss of grain yield for a region? Will such a loss occur if water supply is suddenly disrupted? Or if a new strain of disease occurs? Ironically, such scenarios have been examined for



Note: Cereal production was calculated as the product of harvested area (ha) and yield (Mg ha^{-1}) from the FAO; population values are from the US Census (www.census.gov).

Figure 2.5 *Percentage yearly change in the production (grey line) of the world's principal cereal grains (barley, maize, millet, oats, rice, rye, sorghum and wheat) in relation to percentage yearly change in human population (black line)*

ecological systems (e.g. Lenton et al., 2008), but data for tipping points for agricultural productivity remain largely unexplored.

Critical Needs

There are a number of critical research needs regarding climate, CO_2 and crop production. The following are meant to be illustrative, but not comprehensive, of those needs.

1. Water supply for agriculture

Maximizing crop production to maintain current and projected food needs can only be accomplished via irrigation. In turn, irrigation depends on the availability of freshwater sources including snow and ice collected on mountain ranges. Data suggest that human-induced global warming has significantly shrunk the ice/snowpack in mountain ranges in the American West and elsewhere (Kerr, 2007). Conversely, flooding from precipitation extremes may also result in disruptions, particularly in rainfed areas. Overall, unless

research identifies specific adaptation measures, water extremes will negatively impact food availability for humans.

2. Fertilizer and energy

Maximizing yields will be heavily dependent on adequate supplies of fertilizer, especially nitrogen. Nitrogen supply, in turn, will be highly vulnerable to supplies of fossil fuels, especially natural gas. Research is needed to ensure an ample supply and efficient distribution of fossil-fuel-based fertilizers.

3. Sustainability of crop production

Crop yields are often determined by short-term stress episodes rather than by seasonal mean conditions. Global climate change is predicted to increase climatic extremes including total precipitation, frequency of droughts, as well as episodes of high temperature stress. These stresses could completely offset plant yield increases expected due to rising CO₂. Very little research on agricultural crops' responses to drought and high temperature stress has been conducted at elevated CO₂ levels, so the current crop yield projections are highly uncertain. Research is needed to reduce uncertainty and properly assess future agricultural crop yields.

4. Food safety

Climate change will bring higher temperatures and additional climatic extremes, particularly more extreme precipitation. How will this impact the epidemiology of foodborne pathogens given that *E. coli* and *Salmonella* outbreaks are directly related to temperature? A scientific assessment of the likely impacts and preventive measures is needed.

5. Selection of plant varieties

Initial data suggest that yield selection among existing agricultural crop lines or wild crop biotypes could be used to adapt crops to climatic extremes (drought, temperature) as well as to exploit the rising CO₂ to boost crop yields. At present, however, no systematic evaluation of available geno- or phenotypes has been undertaken. Without such an evaluation, crop yields and agricultural sustainability will be at risk.

6. Invasive species in agriculture

Introduced invasive species can inflict disaster on the sustainability and economic costs of crop production. The total cost of negative impacts of invasive species on agriculture has been estimated at \$138 billion each year (Pimentel et al., 2000). Having few natural enemies in their introduced country, invasives are limited almost exclusively by climate. How will changing CO₂ and increasing minimal temperatures favor the expansion and success of invasive species? For example, Ug99 is a new and potentially invasive strain of wheat stem rust that has overcome existing sources of genetic resistance in the world's wheat crop. If it is introduced, how will a changing climate affect its spread and impact? No historical data are available to determine how current and past climates have altered the biological success of invasive species in crop production. No current global model includes the impact of invasives on crop productivity.

7. Plant species shifts in rangelands

Rangelands will experience regional and local changes in temperature and precipitation. Plants have different sensitivities to temperature, precipitation and CO₂, and research suggests that plant shifts favoring some species over others is under way in rangelands (Morgan et al., 2007). Research is needed to better understand such plant species shifts and their consequences for land management in agriculture. We need to use that knowledge to develop proactive management strategies that will help ranchers and public land managers adapt to climate change.

8. Agricultural trace gases

Climate change is driven by the release of trace or greenhouse gases into Earth's atmosphere, mostly from fossil-fuel burning. Agriculture is involved in all aspects of this problem, being directly affected by climate change. However, agriculture is also a sink or source of greenhouse gases, depending on the particular agricultural enterprise. At present approximately 40 per cent of the greenhouse gases released each year into the atmosphere are captured by terrestrial ecosystems and fixed back into compounds that are not active as greenhouse gases. There is very limited information on how different agricultural practices can be modified to reduce agriculture's negative contribution to the release of greenhouse gases. Research into how different agro-ecosystems and different management practices affect the exchange of greenhouse gases is needed to learn how agriculture can reduce its terrestrial emissions of trace gases to the atmosphere.

9. Beneficial organisms

Many aspects of crop production are linked to the life cycles of beneficial organisms such as bees, earthworms and micro-organisms. There is almost no information on how these beneficial organisms will respond to rising CO₂ or temperature/precipitation changes. For example, if climate change accelerates flowering times, will this result in forced asynchrony between flowering and bee pollination? Research is needed to understand how these changes are likely to affect the abundance and effectiveness of these organisms with respect to crop yields and agricultural sustainability.

10. Communications

For the overwhelming majority of scientists, the vulnerabilities of crop production to climate change are self-evident. Yet in many circumstances, coherent communication of these potential threats to policy makers and the lay public has been unsuccessful. Communication of the current science and expected vulnerabilities to a non-scientific audience is essential to achieve public consensus.

CONCLUSIONS

There is an urgent, critical need to assess the vulnerability of agriculture to climate change. Our current reliance on the Green Revolution paradigm to maintain crop production increases our susceptibility to all aspects of climatic change and uncertainty. However, a number of definitive actions can be implemented to adapt to these changes.

The research gaps and recommendations outlined here are an effective means to begin addressing a complex, multifaceted scientific challenge for agriculture; successful resolution of those challenges will allow us to maintain crop production and global food security in the twenty-first century.

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3 Effects of climate variability on domestic livestock

Terry L. Mader and John B. Gaughan

INTRODUCTION

The livestock industry makes a significant contribution to most rural economies. It accounts for 40 percent of the world's agricultural GDP, and in developing countries can account for as much as 80 percent of GDP (World Bank, 2007a, b). It employs 1.3 billion people and creates livelihoods for one billion of the world's population living in poverty (Gaughan et al., 2009). Livestock production accounts for approximately 70 percent of all agricultural land use and nearly 30 percent of the total land surface use (IPCC, 2007b, c; Neely et al., 2009). Climate changes and related variation in climatic conditions could have significant impact on the economic viability of livestock production systems worldwide. Rötter and Van de Geijn (1999) suggest that any shifts in climatic conditions could affect animal agriculture in four primary ways: (1) feedgrain, production, availability and price; (2) pasture and forage crop production and quality; (3) animal health, growth and reproduction; and (4) disease and pest distributions. As a result of thermal challenges associated with climate variability and change, normal animal behavioral, immunological and physiological functions are all potentially impacted (Nienaber and Hahn, 2007). In addition, metabolic and digestive functions are often compromised when animals are exposed to thermal stress as a result of altered or impaired feeding activity (Mader, 2003). These effects could result in changes in the types of animals and genotypes that are used, changes in facilities and housing utilized for care and management of livestock, and eventually a redistribution of livestock in a region (Gaughan et al., 1999, 2009).

INDICATORS OF THERMAL STRESS IN ANIMALS

Under most environmental conditions, temperature represents a major portion of the driving force for heat exchange between the environment and an animal (Hahn, 1999). However, moisture and heat content of the air, thermal radiation and airflow also impact the total heat exchange (NRC, 1981; Mader and Davis, 2004; Mader et al., 2006). Thus the effective or apparent temperature an animal responds to is a combination of environmental variables (Johnson, 1986; Fox and Tylutki, 1998). Therefore an assessment of animal comfort needs to be derived from indices comprising multiple environmental variables. These indices should represent the effect produced by the heat exchange process, which can alter the biological response associated with changes in environmental conditions. In the case of humans, the useful effect is the sensation of comfort; for animals, the useful effect is the impact on performance, health and well-being. Indices that combine several environmental components have been found to be very useful for characterizing environmental effects on animal productivity and well-being (Mader et al., 1997a, 1999a; Mader and Davis, 2004; Amundson et al., 2006).

Historically, most efforts to develop thermal indices have been for human applications, with emphasis on assessment of comfort, involving both psychological and physiological aspects. The recently revised wind-chill index (WCI), based on combined effects of air temperature (T_a) and wind speed (WS), is now in use in Canada and the USA (Tew et al., 2002). Similarly, a new heat index (HI) has been developed to characterize the combined effects of percentage relative humidity (RH) and T_a (Rothfus, 1990). These two indices tend to be the more common indices used to assess human comfort, but they have some utility for assessing animal comfort as well (FASS, 2010).

While the human-oriented thermal indices focus primarily on comfort and human health, the primary emphasis for domestic animals would be the development of a tool not only to assess animal comfort, but to also support rational environmental management decisions related to performance, health and well-being (Hahn et al., 2001, 2003, 2005). The temperature–humidity index ($THI = 0.8 \times T_a + [(\%RH/100) \times (T_a - 14.4)] + 46.4$) was one of the first developed for animals. It has been extensively utilized under moderate to hot environmental conditions, and has become a *de facto* standard for classifying thermal environments in many animal studies as well as selection of management practices during seasons other than winter (Hahn et al., 2003).

The THI has further been used as the basis for the livestock weather safety index (LWSI; LCI, 1970) to describe categories of heat stress for livestock exposed to extremely hot weather conditions, and can be utilized to define thresholds where the potential for heat stress in livestock exists (FASS, 2010). In connection with extreme conditions associated with heat waves, the THI has been used to evaluate spatial and temporal aspects of their development (Hubbard et al., 1999; Hahn and Mader, 1997). Hahn et al. (1999) derived a classification scheme using a THI-hours approach to assess the magnitude (intensity $\times$ duration) of the heat wave events that put animals at risk. In addition, modifications to the THI have been proposed to overcome the shortcomings related to airflow and radiation heat loads. Based on recent research, Mader et al. (2006) and Eigenberg et al. (2005) have proposed modifications to the THI that include WS and solar radiation (SRAD) in the indices.

Gaughan et al. (2008) developed a heat load index (HLI) as a guide to management of cattle during hot weather ($>25^\circ\text{C}$), following observations of behavioral responses (respiration rate and panting score) and changes in dry matter intake during prevailing thermal conditions. The HLI is based on humidity, WS and predicted black globe temperature. A unique attribute of the HLI was that a base threshold was developed ($HLI = 86$) for unshaded Angus steers with adjustments to the base being made on the basis of genotype, coat color, health status, degree of acclimatization, access to shade, days on feed, and drinking water temperature. The thresholds are used to calculate the accumulated heat load (AHL) to which the cattle are exposed. The AHL is based on the THI-hours concept of Hahn and Mader (1997). The AHL accounts for night-time cooling or a lack of cooling at night. Therefore it gives an indication of the total heat load on the animal, and is a better indicator of thermal stress than a spot measure of HLI. The HLI and the AHL have now been implemented as a heat load warning guide for Australian producers.

The above livestock indices are only relevant under hot conditions. No index incorporates major environmental components that are experienced over a range of both hot and cold conditions. In addition, appropriate environmental stress thresholds are needed

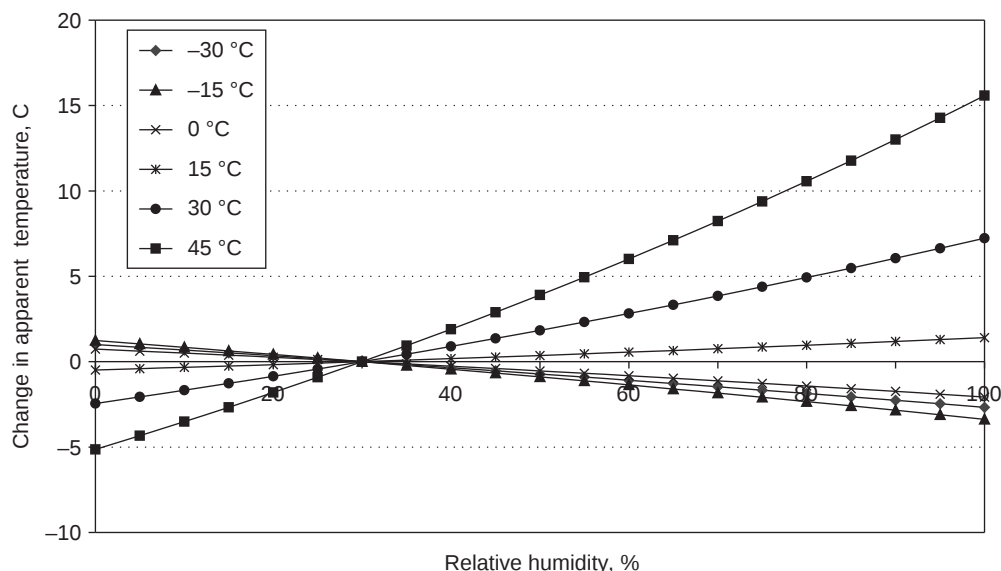


Figure 3.1 Temperature adjustments for the comprehensive climate index, based on percent relative humidity at different ambient temperatures

that are flexible and can reflect stress levels based on environmental conditions, management levels and physiological status. Mader et al. (2010) developed a comprehensive climate index (CCI) and comparable thresholds that utilize multiple environmental variables, incorporated into a continuous index that adjusts temperature for the combined effects of relative humidity, wind speed and solar radiation. The purpose of the CCI was to provide a relative indicator of the environmental conditions surrounding an animal and quantify how SRAD, WS and RH interact with Ta to produce an ‘apparent temperature’ that adjusts Ta for the effects of respective environmental variables. Thus equations were derived to allow adjustments to Ta due to the effects of RH, WS and SRAD. From this analysis, three general algorithms were developed to define the relationship between Ta and RH (Figure 3.1), Ta and WS (Figure 3.2) and Ta and SRAD (Figure 3.3). With this index, low WS results in the greatest change in apparent temperature per unit of WS, regardless of whether hot or cold conditions exist. As WS increases, the change in apparent temperature per unit of WS becomes less. Based on the WCI and algorithms developed by Gaughan et al. (2008), the effect of WS on apparent temperature was found to be similar enough to allow one equation to be utilized under both hot and cold conditions. In addition, the effects of WS at a given temperature may vary with RH, especially under conditions in which animals use evaporative cooling processes to regulate body temperature. Because previous models (Eigenberg et al., 2005; Mader et al., 2006; Gaughan et al., 2008) failed to detect and/or report this effect, no sub-model or algorithms were developed to define this phenomenon.

A multi-factor index would be far superior to a single-factor index for determining environmental effects on animal well-being. For strategic decision making, the goal should be to have an index that is broadly applicable across life stages and species in

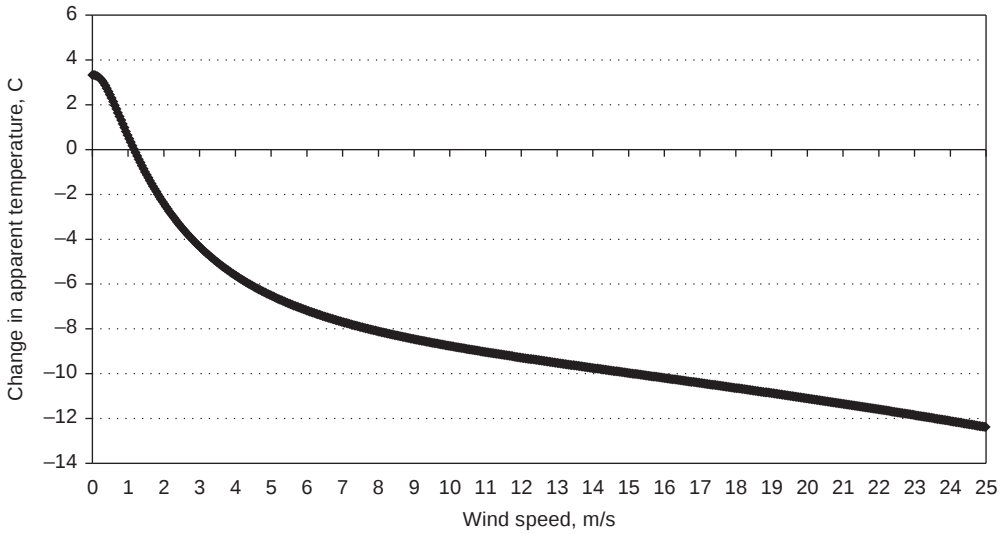


Figure 3.2 Temperature adjustments for the comprehensive climate index based on wind speed

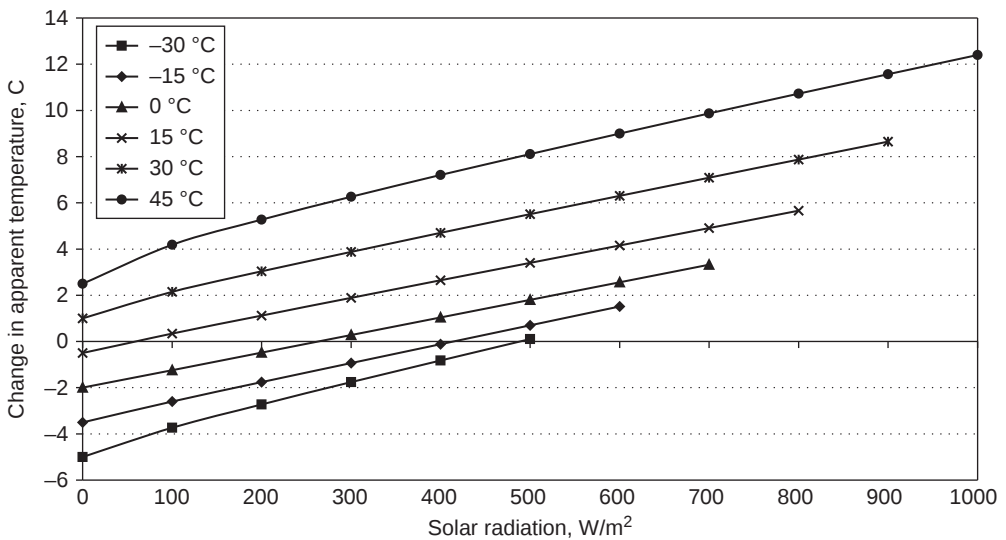


Figure 3.3 Temperature adjustments for the comprehensive climate index based on solar radiation at different ambient temperatures

order to maximize the utility of probability information (Hahn et al., 2003). Indices are needed that are comprehensive in nature, and that allow for greater application across a range of conditions. In summary, the CCI is able to combine the effects of T_a , RH, WS and SRAD into one index, which has potential for use in assessing environmental effects

on animal health, comfort, welfare, maintenance and productivity. From a practical standpoint, the CCI or modifications of the CCI may also have merit in assessing environmental effects on humans, since a significant amount of biological data went into its derivation. Aside from the benefits of obtaining an apparent temperature for assessing comfort level, the continuous range of temperature (-40°C to 50°C) in which the CCI can be utilized would also be useful for calculating projected potential effects of changing climatic conditions.

ANIMALS' RESPONSE TO ENVIRONMENTAL STRESSORS

Changing climatic conditions is not a new phenomenon. Even today global environmental conditions vary considerably. However, the rate at which environmental conditions change, the extent to which animals are exposed to extreme conditions and the inability of animals to adequately adapt to these environmental changes are always a concern (Mader, 2003). Animal responses to environmental challenges vary according to the type and level of thermal stress. Within limits, domestic livestock can cope with most gradual thermal challenges. However, lack of prior conditioning to rapidly changing or adverse weather events most often results in catastrophic deaths in domestic livestock, and losses of productivity in surviving animals. Direct animal effects are primarily a function of heat exchange between the animal and the surrounding environment, as determined by the combined effects of radiation, temperature, humidity and wind speed (Johnson, 1987). Animal phenotypic and genetic variation, management factors (i.e. housing and nutrition), physiological status (stage of pregnancy, stage of lactation, growth rate), age and previous exposure to environmental conditions will alter the response to adverse environmental conditions.

The optimal zone (thermoneutral zone) for livestock production is a range of temperatures and other environmental conditions for which the animal does not need to significantly alter behavior or physiological functions to maintain a relatively constant core body temperature (Mader, 2003). Surrounding conditions directly affect mechanisms and rates of heat gain or loss by all animals (NRC, 1981). In many species 5 to 7 $^{\circ}\text{C}$ deviations from core body temperature may cause death, or at least significant reductions in productive performance (Gaughan et al., 2009). As environmental conditions result in core body temperature approaching and/or moving outside normal diurnal boundaries, the animal must begin to conserve or dissipate heat to maintain homeostasis. This is accomplished through shifts in short-term and long-term thermoregulatory processes (Mader et al., 1997b; Gaughan et al., 2002a, b; Mader et al., 2007). The onset of a thermal challenge often results in declines in physical activity and an associated decline in eating and grazing (for ruminants and other herbivores) activity. Hormonal changes triggered by environmental stress result in shifts in cardiac output, blood flow to extremities and passage rate of digesta. Adverse environmental stress can elicit a panting (hot conditions) or shivering (cold conditions) response, which increases maintenance requirements of the animal and contributes to decreases in productivity (Mader et al., 2002; Davis et al., 2003; Mader and Davis, 2004). As a general rule, for most domestic species respiration rates serve as an early warning of increasing thermal stress, and increase markedly above a threshold as animals try to maintain homeothermy by

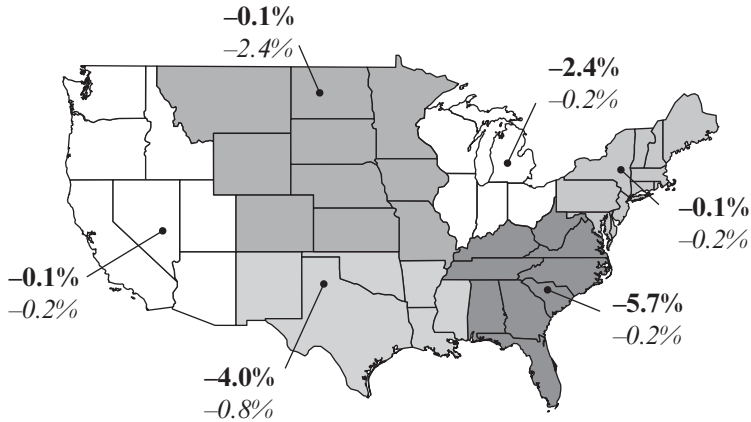
dissipating excess heat. Thus animals pant to increase evaporative cooling. The use of a panting score (Mader et al., 2006) has been found to be an excellent way to detect and monitor heat stress. As body temperatures increase, respiration dynamics continue to change as ambient conditions change (Davis et al., 2003; Mader and Kreikemeier, 2006). Eventually there is a concomitant decrease in dry matter intake (DMI) as body temperature increases, which ultimately results in reduced performance (production, reproduction), health and well-being if adverse conditions persist (Hahn et al., 1992; Mader, 2003).

Depending on the domestic species of livestock, longer-term adaptive responses include hair coat gain or loss through growth and shedding processes, respectively. As a survival mechanism, voluntary DMI increases (after a one- to two-day decline) under cold stress and decreases almost immediately under heat stress (NRC, 1987, 1996). Depending on the intensity and duration of the environmental stress, DMI can average as much as 30 percent above normal to as much as 50 percent below normal. Under extremely hot conditions they may completely lose appetite, while under extreme cold conditions animals may find comfort in maintaining a huddled position with other animals, or by lying down. Due to the discomfort levels associated with standing and accessing feed, DMI and related performance are further compromised under cold stress. However, many adaptive and behavioral adjustments made by the animal when exposed to moderate to extreme environmental conditions often result in lowered animal productivity, and are generally unfavorable to the economic interests of humans. However, these changes are often essential for survival of the animals (Stott, 1981; Gaughan et al., 2009).

Potential Animal Performance Impact of Climate Change

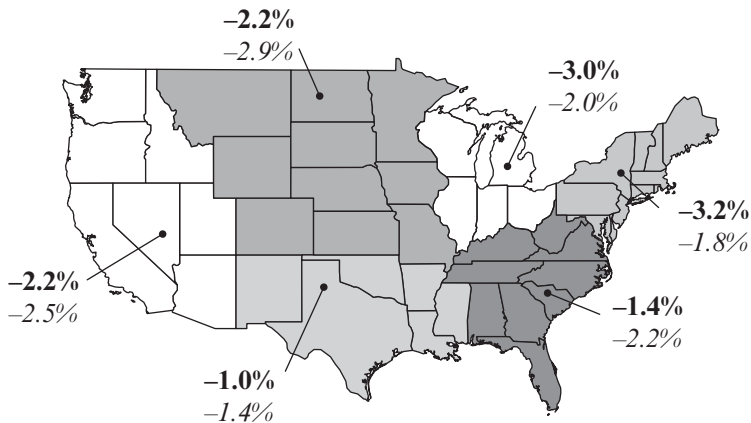
The risk potential associated with livestock production systems due to changing climatic conditions can be characterized by levels of vulnerability as influenced by animal performance and environmental parameters (Hahn et al., 2005). When performance level and environmental influences combine to create a low level of vulnerability, there is little risk. As performance levels increase, the vulnerability of the animal increases, and when this is coupled with an adverse environment, the animal is at greater risk. Combining an adverse environment with high performance pushes the level of vulnerability and consequent risk to even higher levels. Inherent genetic characteristics or management scenarios that limit the animal's ability to adapt to or cope with the environment also puts the animal at risk. At very high performance levels, any environment other than near optimal may increase animal vulnerability.

The potential impacts of climate change on overall performance of domestic animals can be determined using defined relationships between climatic conditions and DMI, climatological data and global climate models (GCM) output. Because ingestion of food/feed is directly related to heat production, any change in DMI and/or energy density of the diet will change the amount of heat produced by the animal (Mader et al., 1999b; Mader and Davis, 2004). Environmental conditions influence heat transfer by the animal; however, animals exposed to the same environmental conditions will not exhibit the same reduction in DMI. Body weight, body condition and level of production also affect DMI. In addition, animals generally prioritize available nutrients to support maintenance needs first, followed by growth or milk production and then reproduction. Thus



Source: Frank et al. (2001).

Figure 3.5 Changes in beef productivity based on the number of days required to reach finish weights from baseline to 2040, beginning June 1 under CGC (**bold text**) and Hadley (*italicized text*) modeled climate



Source: Frank et al. (2001).

Figure 3.6 Percentage change of kg fat-corrected milk (FCM) yield/cow/season (1 June to 31 October) from baseline to 2040, under CGC (**bold text**) and Hadley (*italicized text*) modeled climate

4.8 days (above the 127-day baseline value) or 3.8 percent, costing producers US\$43.9 million annually (Figure 3.5). Climate changes predicted by the Hadley model resulted in a loss of 2.8 days of production, or 2.2 percent. For dairy, the projected CGC 2040 climate scenario would result in a 2.2 percent (105.7 kg/cow) reduction in milk output and cost producers US\$28 million annually (Figure 3.6). Production losses associated with the Hadley scenarios would average 2.9 percent and cost producers US\$37 million

annually. Across the entire USA, percentage increase in days to market for swine and beef and the percentage decrease in dairy milk production for the 2040 scenario averaged 1.2 percent, 2.0 percent and 2.2 percent, respectively, using the CGC model, and 0.9 percent, 0.7 percent and 2.1 percent, respectively, using the Hadley model. For the 2090 scenario, respective changes averaged 13.1 percent, 6.9 percent and 6.0 percent, using the CGC model, and 4.3 percent, 3.4 percent and 3.9 percent, using the Hadley model. For these scenarios it should be noted that production losses for the dairy sector were generally not as great as those found for beef and swine in the south and southeast parts of the USA. This could be partially due to the equation used, which defines a linear relationship between feed intake and ambient temperature. This relationship in reality may be slightly curvilinear, particularly if elevated ambient temperatures are sustained, with the rate of decline in feed intake increasing with increasing temperature. This would produce a result more similar to that found for beef and swine. In addition, there is an increase in maintenance energy requirements in cattle reared under hot conditions (NRC, 1996), which also would result in additional losses of production.

Estimates of livestock production efficiency suggest that the negative effects of hotter weather in summer outweigh the positive effects of warmer winters (Adams et al., 1999). Thus it is very likely that a portion (estimated to be ~50 percent) of the declines in domestic livestock production during the summer due to global warming can be offset by improvements in productivity during the winter, provided winter environmental conditions are not more adverse under warming conditions. In addition, high-producing animals will most likely be affected to a greater extent by global climate change than animals with lower production levels. A production area in which global climate change may have negative effects that are not offset by positive winter effects are conception rates, particularly in cattle, in which the breeding season primarily occurs in the spring and summer months. Hahn et al. (1995) reported that conception rates in dairy cows were reduced 4.6 percent for each unit change in the THI. Amundson et al. (2006) reported a decrease in conception rates of *Bos Taurus* cattle of 3.2 percent for each increase in THI above 70, and a decrease of 3.5 percent for each increase in temperature above 23.4 °C. Clearly, increases in temperature and/or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions. However, Amundson et al. (2006) also reported that minimum daily temperature was the environmental variable that has the closest relationship to pregnancy rate in beef cattle, but that under current central USA weather conditions, cattle do adapt to changing climatic conditions given sufficient time. Independent of climate change, geographical location and seasonal breeding patterns are significant factors that influence conception rates (Sprott et al., 2001).

In an effort to maintain optimum levels of production, climate change will probably result in livestock producers selecting breeds and breed types that have genetically adapted to conditions similar to those associated with climate change. However, in warmer climates, breeds that are often found to be more heat tolerant are those that generally have lower levels of productivity, which is probably the mechanism by which they were able to survive as a dominant breed for that region. In addition, climate change and associated variation in weather patterns will probably result in more livestock being managed in or near facilities that have capabilities for imposing microclimate modifications (Mader et al., 1997a, 1999a, 2007; Gaughan et al., 2002b). In general, domestic livestock can cope with or adapt to gradual changes in environmental conditions; however,

rapid changes in environmental conditions or extended periods of exposure to extreme conditions drastically reduce productivity and are potentially life threatening.

Indirect effects of climate change on animal productivity will be the changes that may occur to feed and forage supplies. Excellent reviews of the effects of climate change on pastoral systems are provided by IPCC (2007a, b), Hauser et al. (2009), Neely et al. (2009) and Thornton et al. (2009). In general, climate change can be expected to change herbage growth and quality, pasture species composition and the incidence and intensity of rain events, as well as drought (Hopkins and Del Prado, 2007). The impact of climate change may include deterioration of pasture quality towards poorer quality as a result of the change in ratio of C₃ to C₄ (plants). Of particular concern are the invasive C₃ weeds (Hauser et al., 2009), as well as the potential for C₄ grasses to diminish (IPCC, 2007b). However, an extended growing season and increased CO₂ levels will probably increase forage yield, depending on rainfall pattern and drought conditions, although quality may be compromised if forage growth is not properly managed. In addition, any shifts in climatic conditions may promote insect movement and migration, as well as alter overwintering conditions for parasites and insects that are potentially harmful to forage production and grain cropping systems.

Impact of Climate Change on Animal Health

Another area of concern is the influence of climate change on diseases and parasites that affect domestic animals. Incidences of disease, such as bovine respiratory disease, are known to be increasing (Duff and Gaylean, 2007). However, causes for this increase can be attributed to a number of non-environmentally related factors, including animal transport and concentration. As for parasites, changing climatic conditions may result in similar insect migration, and overwintering scenarios that are observed in cropping systems may be found for some parasites that affect livestock. Climate changes can affect the health of livestock and poultry both directly and indirectly. Direct impacts include temperature-related illness and death, as well as the morbidity of animals during extreme weather events, while indirect impacts include the influence of climate on microbial density and distribution, distribution of vector-borne diseases, host resistance to infections, food and water shortages or foodborne diseases (Baylis and Githeko, 2006; Gaughan et al., 2009; Thornton et al., 2009).

Baylis and Githeko (2006) describe how climate change could affect parasites and pathogens, disease host and disease vectors for domestic livestock. The potential clearly exists for increased rate of development of pathogens and parasites due to spring arriving earlier, coupled with warmer winters, which allows for greater proliferation and survivability of these organisms. For example, bluetongue was recently reported in Europe for the first time in 20 years (Baylis and Githeko, 2006), although shifts in appearance of pathogens and parasites may move longitudinally as growing seasons and/or regions shift in the directions of the poles. Nevertheless, regional warming and changes in rainfall distribution may lead to changes in the spatial or temporal distributions of those diseases sensitive to moisture, such as anthrax, blackleg, hemorrhagic septicemia and vector-borne diseases. These diseases, as shown by climate-driven models designed for Africa, may decline in some areas but spread to others (Baylis and Githeko, 2006). Aside from climate effects on pathogens, hosts, vectors and epidemiology, Thornton et al.

(2009) indicate that climate change may influence the abundance and/or distribution of the competitors, predators and parasites of vectors themselves, thus influencing disease patterns. Gaughan et al. (2009) reported a higher incidence of ketosis, mastitis and lameness in dairy cows as a result of hotter weather. Interestingly, studies have been unable to consistently document any adverse relationships between heat stress and overall immune function in cattle, chickens or pigs; however, an additional concern related to warmer climates is the effect on growth of mycotoxin-producing fungi, particularly if moisture conditions are favorable (Gaughan et al., 2009).

ANIMAL MANAGEMENT, MITIGATION AND ADAPTATION

Changes in climate induced by increasing CO₂ levels are primarily manifested as increases in air temperature, which reduces livestock production during the summer season with partial offsets during the winter season. Current management systems usually do not provide as much shelter to buffer the effects of adverse weather for ruminants as for non-ruminants. From that perspective, environmental management for all domestic livestock in general, but especially for ruminants exposed to global warming, needs to consider (1) general short- and long-term changes in environmental conditions; (2) changes in night-time conditions that do not allow for adequate cooling; and (3) increases in the occurrence of extreme events (e.g. higher daily maximum temperature and more/longer heat waves).

Rötter and van de Geijn (1999) suggest that impacts of heat stress may be relatively minor for the more intensive livestock production systems where some control can be exercised over the exposure of animals to climate. In general, domestic livestock are remarkable in their adaptive ability by mobilizing coping mechanisms when challenged by environmental stressors. Breeding and selection criteria for domestic livestock need to be considered in the context of climate change. Depending on location, climate change may have both negative and positive-negative impacts. However, extreme events, whether climate change related or not, generally always have adverse effects and require implementation of pre-planned animal management practices (emergency) to minimize impact. The capabilities of livestock managers to cope with the effects are quite likely to keep up with the projected rates of change in global temperature and related climatic factors. However, coping will entail costs such as application of environmental modification techniques, use of more suitably adapted animals or even shifting animal populations.

Beede and Collier (1986) suggest three management options for reducing the effect of thermal stress in cattle, which have application for all livestock and poultry. The options are: (1) physical modification of the environment; (2) genetic development of breeds with greater heat tolerance; and (3) improved nutritional management during periods of high heat load. In order to take advantage of positive changes or reduce the impact of negative changes, the entire livestock system will most likely have to adapt to the change. Improved genetics (including suitability to the environment) and improved management may go a long way to take advantage of changes or minimize the impact. As is the case in most livestock systems today, housing and microclimate modification considerations (sunshades, evaporative cooling by direct wetting or in conjunction with mechanical ventilation), improvements in nutritional management and disease control, and use

of new technologies will need to be assessed as change dictates (Gaughan and Mader, 2007; Mader et al., 2008; Gaughan et al., 2009). Included in that assessment will be the cost of implementation of altered or new processes, which will be particularly pertinent in less developed and less intensive production systems. An additional consideration is that modifying management and/or genetics for one environmental extreme may have adverse effects if the livestock are exposed to the opposite environmental extreme. Also, animals with the genetic and metabolic capabilities for high levels of productivity are typically less heat tolerant than moderate or low-producing animals due to the high feed intake and metabolic heat load associated with the higher-producing animals.

A final management issue related to climate change is water availability and utilization. Water has been recognized as one of the most important nutrients for life. It plays a key role in virtually all biochemical reactions in the body and is also considered to be one of the quickest and most efficient methods to reduce body temperature during warmer periods. During heat waves, normal heat exchange is impeded, which affects the thermal equilibrium of the animal and its performance. Per unit of feed intake, water intake is generally two times greater under hot conditions than under cold conditions (Kreikemeier and Mader, 2004). The interaction of climatic factors, types of diet, animal breed, animal weight, production status and physiological strategies adopted by each animal influences individual animal water intake. In addition, drinking behavior is complex and influenced by a number of social and physical factors, including degree of competition for water space, group social order, water availability and accessibility and water quality.

CARBON FOOTPRINT AND LIVESTOCK PRODUCTION

With the world population likely to increase from 6.7 billion to 9.2 billion by 2050 (UN, 2007), the demand for food, fuel, feedstuffs, land and water will present many challenges to agriculture. By 2020, the global meat demand is expected to increase by 58 percent, egg production will increase by 30 percent, and poultry, beef and pig meat demand will increase by 85, 80 and 45 percent from 1995 levels, respectively (FAO, 2004). Economic growth and changing lifestyles are also creating a growing demand for meat products in developing countries, achieving an annual growth rate of 5 percent (Smith, 2007). However, as a result of levels of anthropogenic greenhouse gas (GHG) components produced from livestock, estimates of the livestock carbon footprint are of interest. For agriculture, the primary GHGs of interest are methane and nitrous oxide. Methane is largely derived from enteric fermentation, a normal part of digestion of feed and fiber particularly for ruminant animals (cattle, goats, sheep, deer, bison etc.), while methane and nitrous oxide are both generated from animal waste. Globally 13.5 percent of all GHG are derived from agriculture, while in the USA only 7 percent of the GHGs are derived from agriculture (IPCC, 2007b, c; USDA, 2008). In general, enteric fermentation and animal waste emissions constitute about 35 percent of the agricultural GHG pool, while emissions associated with grasslands and grazing systems contribute about 20 percent to the agricultural GHG pool (USDA, 2008). Among species, beef cattle, dairy cattle, swine, horses and poultry contribute 61.5, 19.8, 8.1, 4.2 and 1.2 percent to the pool of GHG from livestock in the USA, respectively (USDA, 2008). In the USA, the sheep

and goat population is very small and contributes very little to the US carbon footprint; however, globally that is not the case. Worldwide there are 1.5 billion cattle and buffalo, and 1.8 billion sheep and goats (FAO, 2006).

Annually, beef cattle (dairy not included) in the USA produce approximately 168.3 million metric tons (Tg) of greenhouse gas CO₂ equivalents produced from 86.5 million head (USDA, 2008). In comparison, the calculated emissions for bison, based on the estimated sustained population of 65 million that were roaming the Great Plains in North America in the mid-1800s, were approximately 150 TgCO₂ equivalents. When assessing production systems that are environmentally friendly, one must keep in mind resource availability and overall efficiencies of the system. The carbon footprint per unit of production has a close relationship to efficiency of production. Over the past few decades, efficiencies of production have improved markedly in all phases of livestock production. For instance, the kg of CO₂ equivalents produced per kg of milk from dairy herds in the USA has been reduced from 3.66 in 1944 to 1.35 in 2007 (Capper et al., 2009). Similarly, the Canadian beef industry GHG-CO₂ equivalent emissions decreased 36.6 percent per unit of beef produced from 1981 to 2001 (Verge et al., 2008). This enhanced efficiency is due in part to a change in feeding as well as management practices. Utilizing a grain-based cattle finishing system versus a fiber-based cattle feeding system lessens time on feed, improves feed conversion and lowers the overall carbon footprint. In general, fiber digestion produces approximately twice the amount of GHGs, mostly methane, as grain or starch digestion. For instance, in the USA the carbon footprint of a fiber-based finishing system is approximately 50 percent greater than a grain-based finishing system when cattle are grown to comparable finish weights. By contrast, in Australia the carbon footprint for grass-finished cattle was only 20 percent greater than that of grain-finished cattle, based on grass-finished cattle having approximately 25 percent lower weights at slaughter than grain-finished beef (Peters et al., 2010). Peters et al. (2010) also found that sheep utilized for meat production had a 20 to 30 percent lower carbon footprint than cattle.

Domestic livestock serve a vital purpose in functional food production systems. Sustainable grassland ecosystems will always be best utilized by herbivores. Depending on the socioeconomic structure and relative feed costs, livestock producers will continue to utilize production systems that use varying ratios of starch-based and fibrous feed sources (i.e. grain versus pasture utilization), particularly for ruminants.

Rangelands are estimated to store up to 30 percent of the world's soil carbon, not including above-ground biomass, and have additional capacity to sequester considerably more carbon if properly managed (Neely et al., 2009). In addition, processors of raw cereal grains, fruits and vegetables utilize ruminants to dispose of many of the fibrous by-products as opposed to dumping product in landfills or elsewhere. In general, ruminants are very adaptable to changing environmental conditions and are an excellent species for prairie and grasslands management, as well as for the degradation and disposal of food by-products.

CONCLUSION

In general, most domestic livestock are remarkable in their adaptive ability when challenged by moderate levels of environmental stressors. Under adverse environmental

conditions, strategies need to be implemented to minimize the stress but not necessarily completely eliminate it. Buffering the animal against environmental elements allows adaptation to occur without incurring excess costs. However, duration and intensity of potential adverse climatic events are of concern with respect to the coping and/or adaptive capabilities of animals. A greater understanding of the animals' responses to environmental challenges is essential to successful implementation of strategies to ameliorate negative impacts of climate change. Livestock managers will need to be proactive and consider resource availability (feed, water, health care, animals, land base, people) when adopting climate change mitigation strategies. According to Gaughan et al. (2009), the most important element of proactive environmental management is to reduce risk through preparation. Included in the preparation process is appropriate government intervention for education and training, development of strategic plans for adjusting to changing conditions, recognition of animal needs and potential stress levels, adopting strategies to minimize and/or mitigate the stress and selection of animals, and management strategies that are compatible with the production enterprise. Furthermore, caution should be exercised so that changing climatic conditions are not overcompensated for. An approach is needed that will allow appropriate livestock production changes to occur in a timely manner while avoiding undue disturbance of the socioeconomic structure of the livestock production system.

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4 From the farmer to global food production: use of crop models for climate change impact assessment

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INTRODUCTION

Although there is growing consensus over the reality of climate change (IPPC, 2007), accurately predicting climate change impacts remains a daunting task. Climate change impacts on crop production are particularly hard to predict and assess (Hansen et al. 2006; Lobell and Ortiz-Monasterio, 2006; Iglesias et al., 2011; Mendelsohn and Dinar, 1999; Tubiello and Ewert, 2002; Challinor et al., 2009). In part this is because the data and modelling tools tend to be more robust at the local level (Hansen and Jones, 2000) than at the regional level. The resulting range of predicted impacts on crop production is extensive, not least because of the inherent difficulties associated with projecting and evaluating the numerous sources of uncertainty present in any study of climate change impacts.

Several hundred studies have approached the estimation of climate change impacts on agricultural and food production from different points and have included physiological considerations (Tubiello and Ewert, 2002; Long et al., 2006), productivity and management considerations (Olesen and Bindi, 2002; Porter and Semenov, 2005; Iglesias et al., 2007; Easterling et al., 2003; Reidsma et al., 2007), estimations of the effects of pests and diseases (Rosenzweig et al., 2006) and interactions with water (Alcamo et al., 2007; Iglesias et al., 2011). All of these studies, both named and not named, have contributed to our understanding of how different analytical tools may be used for impact assessment, their strengths and limitations, and the sources of uncertainty that derive from the methodologies used.

The objective of this chapter is to provide an overview of the main tools and models currently used to assess climate change impacts on crop productivity and their economic consequences. The chapter also reviews the methods for dealing with changes in spatial scales, uncertainty and climate variability, which are three of the main challenges that researchers confront when assessing climate change impacts.

The chapter is organized as follows: the next section presents an overview of climate change impacts on agricultural and food production. Then we discuss the different kinds of models and tools that are used for estimating climate change impacts on agriculture; these models and tools are divided into two main groups: those used to assess impacts on crop productivity and those used to assess the economic effects of climate change. A further section describes the different methods used for dealing with spatial scales, uncertainty and climate variability. The final section provides conclusions for further studies.

CLIMATE CHANGE IMPACTS ON AGRICULTURE AND FOOD PRODUCTION

Global food production is a very complex system in which ecological and socioeconomic variables act together at different spatial scales (Lobell et al., 2008; Mendelsohn et al., 2001). The assessment of climate change impacts on food production must deal with this complexity and the interconnections that exist between a number of key factors; it must also recognize that agriculture is a key contributor to climate change (EEA, 2008).

The variables that influence crop production are both biophysical and socioeconomic in nature, and include those related to policy processes (Figure 4.1). Some biophysical determinants such as temperature, rainfall, solar radiation, CO₂ and soil are intuitively understood to be essential components of crop productivity (see e.g. Jablonski et al., 2002; Olesen and Bindi, 2002; Cramer et al., 2001; Tubiello et al., 2007; Challinor et al., 2003). But monthly or annual averages are not the only factors that must be considered (Katz and Brown, 1992). Extreme events and their frequency can also determine local and regional productions (Iglesias et al., 2009; Sivakumar et al., 2005). At the same time, interannual variability has a considerable impact on the economic performance of the agricultural sector (Adams et al., 2003). Finally, pests and diseases can also determine crop yields and farm economic performance, and may be influenced by the same biophysical variables that affect crop productions (Rosenzweig et al., 2001).

From the socioeconomic point of view, markets have a strong influence on food produc-

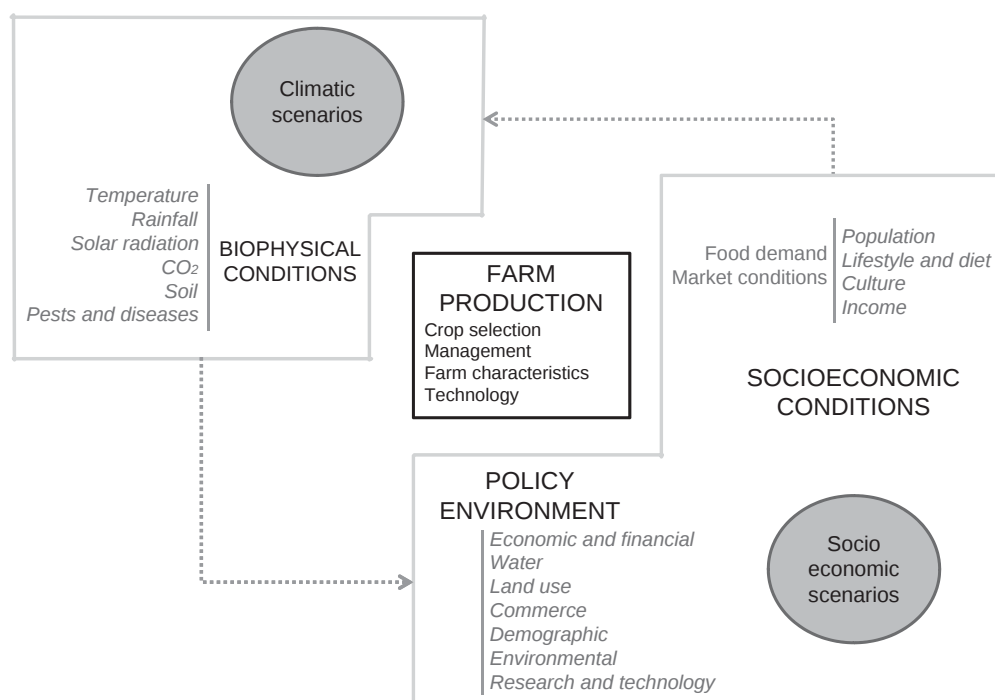


Figure 4.1 Key biophysical and socioeconomic variables that influence farm production

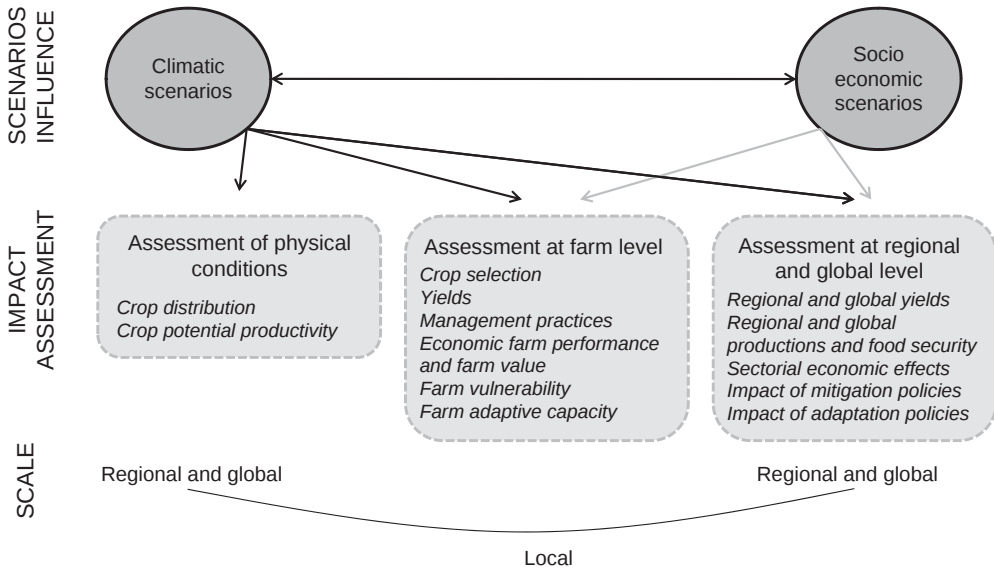


Figure 4.2 Impact assessment, scenarios and scale

tion. Food demand does not depend solely on population size; it is also related to lifestyle and diet, which in turn are influenced by socioeconomic development (Mendelsohn et al., 2001). At the same time, crop production is related to input prices and a wide set of policies that affect agricultural systems. Other factors that have a strong influence on crop productivity include economic and financial performance, the status of water resources (Döll, 2002; Alcamo et al., 2007; Iglesias et al., 2011), land use trends (Olesen and Bindi, 2002), trade patterns (Parry et al., 2004), environmental research and technological development, and demographic conditions (Alexandratos, 2005). The positive trends in crop yields of the past decades impose an additional difficulty when estimating the effects of climate change when socioeconomic and technological conditions are also in flux (Hafner, 2003).

Farmers respond to these external variables through management decisions. Therefore the influence of management on crop productivity is the combined result of input use and agricultural practices. As a result there is a growing recognition that farm-level performance can be different, even under identical climatic conditions, because of particular farm characteristics such as size, shape and financial or technological capacity. In consequence, farm characteristics influence adaptive capacity at the farm level (Reidsma et al., 2007) (Figure 4.1).

The assessment of climate change impacts on agriculture can be performed using a number of different approaches. These approaches may consider an estimation of the changes in potential crop distribution, productive potential, crop selection, yields, management practices (including input use), economic farm performance, global requirements of inputs (including irrigation water) (Döll, 2002; Alcamo et al., 2007), regional and global productions, sectorial economic effects, farm adaptive capacity, vulnerability to changing conditions or impact of mitigation and adaptation policies. As Figure 4.2 shows, these approaches are established at different levels of analysis and

are therefore analysed at different scales. Figure 4.2 also shows how different methods for assessing impacts require information from different types of scenarios. The figure also illustrates that the different assessments provide information at different spatial scales. These observations indicate that particular models and tools are suited for particular types of assessments, and that the availability of data will also determine the extent to which those particular models and tools are applicable in different cases (Figure 4.2).

TOOLS AND MODELS FOR ESTIMATING CLIMATE CHANGE IMPACTS ON AGRICULTURE

Models are widely used to estimate climate change effects on agriculture because of the impracticality of performing controlled experiments to observe interactions of climatic and human factors. Many methods are currently used to estimate climate change effects. These methods vary in scope, approach, variables considered, data needs, scale of analysis and outcomes produced. Additionally, they can be used alone or combined when the outcome of one tool is used as an input for another or to compare results under different hypotheses. Given the extensive array of methods, this section presents the main families of models and tools that are used to evaluate effects of climate change on agriculture.

Here we divide the main methodological tools into two groups. The first includes models and tools oriented towards crop productivity and crop potential based on plant physiology and crop yields; the second includes those methods that consider markets and economic performance of the agricultural sector, as well as tools oriented towards estimating global, national or regional production and food security.

Both groups consider management at farm level but use different approaches to do so. In the first group the main objective at farm level is to maximize yield, while in the second group the goal is to maximize monetary profit. Therefore the first set tends to overestimate input use and actual yields in developing countries while the second deals with a wider set of socioeconomic variables that are difficult to predict (economic development, food demands and their driving forces, trade and custom policies, among others). Frequently both groups are nested so that the output from the yield-maximizing models becomes an input in profit-maximizing models. Although there are clear advantages to this strategy, the resulting uncertainty needs to be recognized.

MODELLING CHANGES IN CROP PRODUCTIVITY

There is a wide range of methods to evaluate crop productivity. Each method yields information on different types of impacts. For example, simple agroclimatic indices can be used to analyse large-area shifts of cropping zones, whereas process-based crop growth models are used to analyse changes in crop yields. Effects on production, income or employment are assessed using economic and social forms of analysis, as discussed in the following subsections.

Table 4.1 Summary of the use of agroclimatic indices

Assessment of physical conditions	Observations	References
Crop distribution	Main use of this group	Carter et al. (1991a, 1991b); Carter and Saarikko (1996); Holden and Brereton (2004) See 'Production functions'
Crop potential productivity / yield	Simplest case of production functions	
Farm-level assessment Crop selection	Crop selection based on potential yields	See 'Production functions'

Agroclimatic Indices

Agroclimatic indices are based on simple relationships of actual or potential crop suitability to climate (e.g. identifying the temperature thresholds of a given crop or using accumulated temperature over the growing season to predict crop yields) (Carter and Saarikko, 1996; Carter et al., 1991; Holden and Brereton, 2004). They are used to predict the potential distribution of crops based on critical values of basic (precipitation or temperature) or derived climatic variables (e.g. accumulated temperature) (Carter and Saarikko, 1996).

This type of empirically derived coefficient is especially useful for broad-scale mapping of areas of potential impact. Indices frequently used to measure moisture include the effective temperature sum (Carter et al., 1991), Thornthwaite's precipitation effectiveness index, Palmer drought index, relative dryness index and standard precipitation index. Table 4.1 summarizes the use of agroclimatic indices for the assessment of physical conditions and farm-level assessments.

Process-based Crop Models

Process-based models use simplified functions to express the interactions of crop growth and the major environmental factors that affect crops (i.e. climate, soils and management), many of which have been used in assessments of climate impacts. Most were developed as tools in agricultural management, particularly for providing information on the optimal amounts of input (fertilizers, pesticides and irrigation) and their optimal timing. Dynamic crop models are now available for most of the major crops. In each case, the aim is to predict the response of a given crop to a specific climate, soil and management factor.

Process-based crop models are capable of providing a mechanistic description of crop responses (Carter and Saarikko, 1996). Most process-based crop models are deterministic, therefore variance of results is due only to variation of input data (Faivre et al., 2009). They are built based on a set of equations where dependent variables related with biological and environmental factors have been correlated with the main biological processes. From a mathematical point of view they are based on a numerical integration of variables over a short period of time (hour, day or week). They consist of at least three modules (Faivre et al., 2009): a soil module oriented to nutrient transfer, a plant module

that represents plant growth and the main phenological stages, and an atmosphere module that represents evapotranspiration (including plant transpiration). Independent variables considered depend on each model but typically include: (a) biophysical variables: temperature (usually based in minimum and maximum daily values), radiation, CO₂ atmospheric concentration, rainfall, soil nutrients and relevant characteristics to nutrient interchange and soil water-holding characteristics, and (b) management variables: cultivar, planting date, planting density and depth and irrigation water and fertilization practices (dates and amounts). Other variables such as wind speed, relative humidity or dewpoint temperature, open pan evaporation and soil temperature are sometimes needed or estimated based on primary weather variables.

Clearly, these models are very data intensive. Equations require site-specific calibration and daily weather data. The availability of weather data is a constraint in climate change assessments and has led to the development of weather generators that estimate daily data for future scenarios based on monthly averages. The most commonly used are WGEN, Simmeteo and CLIGEN (see Semenov et al., 1996; Hoogenboom, 2000). On the other hand, a major advantage of these models is their ability to capture non-linear relationships (Challinor et al., 2003).

DSSAT, EPIC and WOFOST model packages are the tools most frequently used as process-based models. DSSAT is a decision support system used to facilitate simulations of crop responses to management. The DSSAT models have been used widely for evaluating climate impacts in agriculture at different levels, ranging from individual sites to wide geographic areas (see Rosenzweig and Iglesias, 1994) since the early 1990s. This type of model structure is particularly useful in evaluating the adaptation of agricultural management to climate change. The DSSAT software includes over 20 models for the main food and fibre crops; with funding provided from USAID, many of the models were specifically developed for climate change impact studies and have been calibrated and validated in a few hundred sites over different agroclimatic regions.

The EPIC model (Erosion–Productivity Impact Calculator; Sharpley and Williams, 1990) and its derived model, ACCESS II, incorporate simplified crop growth functions that respond to climate, environment and management; they have been used in some climate impact assessments (Tan and Shibasaki, 2003; Gibbons and Ramsden, 2005). Contrary to DSSAT models, early versions of this model cannot calculate specific yields for individual crops and it does not consider the positive effects of CO₂ levels on yields. Therefore some adjustments are made when differentiated values are needed (based on Kimball et al., 1983, for example). Because this is a serious constraint in climate change assessment, EPIC was modified to include CO₂ fertilization (Easterling et al., 2003). In addition, it considers tillage practices.

The WOFOST model suite is generic and includes model parameters for certain crops. There are several versions of the model under continuous development (Supit et al., 1994). This model is used in Europe to estimate annual regional crop yields using remote sensing (Rabbinge and van Diepen, 2000). Other models with similar characteristics include GOSSYM, DAYSY, CROPSYST, CLIMCROP (Olesen et al., 2000), STICS and SUCROS, and many crop-specific models. Crop models like these simulate optimum management practices and assume a good technical knowledge of farmers (Adams et al., 2003) or unlimited input use (Quiroga and Iglesias, 2009). As a consequence, real yields tend to be smaller than simulated yields (Chipanshi et al., 2003; Reidsma et al., 2010).

Table 4.2 Summary of the characteristics of process-based crop models

Assessment of physical conditions	Observations	References
Crop distribution	Crop is suitable when it ripens in 80% of the years	Saarikko (2000)
Crop potential productivity / yield	When optimal management and no limits to water and inputs are assumed	See 'Yield calculation'
Farm-level assessment		
Yields and farm vulnerability	This is the main application of this group of models	Saarikko (2000); Tan and Shibasaki (2003); Adams et al. (2003); Carbone et al. (2003); Gibbons and Ramsden (2005)
Yes		Iglesias et al. (2000)
Management practices and adaptive capacity	Management scenarios about fertilizer use water use technological substitution	Rosenzweig et al. (2004)
Yes		Easterling et al. (2003)
Regional and global assessment		
Regional and global yields. Impact of mitigation policies	Based on global changes on yields; coupled with macroeconomic modelling	Tan and Shibasaki (2003)
Input needs	Water	Döll (2002); Döll and Hauschild (2002); Alcamo et al. (2003); Rosenzweig et al. (2004)

Process-based crop models have also been used to estimate water demands for agriculture by integrating them with water use models like WATBAL for water supply and/or WEAP for water demand forecasting, planning and evaluation (Rosenzweig et al., 2004). The United Nations Food and Agriculture Organization (FAO) has developed two crop models: CROPWAT, an empirical irrigation management model, and Aquacrop (Raes et al., 2009), a process-based model to simulate crop yield response to water. In both models net irrigation demand (the balance between the crop evapotranspiration and the water available for the crop) can be calculated for more than 1000 sites around the world included in the FAO database. All of these models can be adjusted to include irrigation efficiency for each region (Rosenzweig et al., 2004). Another model for estimating water irrigation requirements is WaterGAP (Döll, 2002; Alcamo et al., 2007). Table 4.2 summarises some characteristics of process-based crop models.

Production Functions

Complex multivariate models attempt to provide a statistical explanation of observed phenomena by accounting for the most important factors (e.g. predicting crop yields

on the basis of temperature, rainfall, sowing date and fertilizer application). Statistical models may be developed from empirical data or from a combination of empirical data and simulated data that represent the causal mechanisms of agricultural responses to climate. Models built on the basis of present-day climatic variations are well understood and relevant for engaging stakeholders. However, their limited ability to predict effects of climatic events that lie outside the range of present-day variability is a weakness when considering future climate change or changes in crop systems (Mearns et al., 1997). The method may also be criticized for being based on statistical relationships between factors rather than on an understanding of important causal mechanisms. However, where models are founded on a good knowledge of the determining processes and where there are well-founded grounds for extrapolation, they can still be useful predictive tools in climate impact assessment. This approach has been implemented by Lobell et al. (2008) to prioritize adaptation strategies to climate change and by Quiroga and Iglesias (2009) for a regional comparison of risks for the management of Mediterranean crops.

Nevertheless, some authors have criticized the simplistic relationships between temperature and yields included in the models. This problem arises when scenarios with major climate changes are used. In these cases, future temperatures can be on the limits of current natural variability, and therefore statistical correlation may not be useful (Lobell and Field, 2007).

Multiple regression models can be developed to represent process-based yield responses to these environmental and management variables. Yield functions have been used to evaluate the sensitivity and adaptation to climate in numerous regions and countries, including Spain (Iglesias et al., 2000), as well as globally (Parry et al., 2004). Iglesias et al. (2009) have followed a combination approach of process-based models and statistical functions of yield responses to develop crop production functions across Europe for policy analysis. In other cases, process-based models are used to test results in selected locations (Lobell et al.; 2008). Table 4.3 summarizes some characteristics of production functions.

ASSESSING THE ECONOMIC EFFECTS OF CLIMATE CHANGE FOR REGIONAL AND GLOBAL PRODUCTION

Assessing the regional and global effects of changes in crop productivity and management is more complex than simply scaling up changes in crop yields at farm level. Although some changes in spatial scale are needed, the process is substantially more complex since it involves input prices, trade systems, relationships between supply and demand at different spatial and administrative scales, customs policies, as well as many others.

These tools, which seek to maximize profit, need crop yields as input or can be built separately based on climate and other variables (soil, management, among others). Therefore, in the first case, they are linked with tools and models analysed in the previous section. In the second they are utilized independently unless some kind of comparison is performed. The three groups of approaches are discussed below.

Table 4.3 Summary of the characteristics of production functions

Assessment of physical conditions	Observations	References
Crop distribution	Based on attainable yields that are 80% of maximum yield	Fischer et al. (2001, 2002, 2005)
Crop potential productivity / Yield	Correlated with process-based simulations	Fischer (2001, 2002, 2005)
Farm-level assessment Yields	Relationships with observed yields Relationships with calculated yields from process-based crop models	Challinor et al. (2003) Quiroga and Iglesias (2009); Iglesias and Quiroga (2007); Lobell et al. (2008) Iglesias et al. (2000); Parry et al. (2004)
Regional and global assessment		
Regional and global yields.	Yield for multiple crops statistically related with climate data	Saarikko (2000)
Impact of mitigation policies Yes		Lobell et al. (2008)
Regional and global productions and food security Yes	Usually production change is related with yield change. Therefore there is an implicit assumption of no changes in agricultural land or management	Lobell et al. (2008)
Sectorial economic effects Yes	Used together with macroeconomic models to assess economic effects	Quiroga and Iglesias (2009)
Impact of adaptation policies Yes	Changes in crops based on predicted effects on yields	Lobell et al. (2008)

Ricardian Approach

This family of methods considers a particular case of production functions oriented to analyse economic effects (Mendelsohn et al., 1994; Mendelsohn et al., 2004). They build statistic relationships between climate and other independent variables to obtain farm land value or farm revenue (dependent variable) (Mendelsohn et al., 1994). Another outcome is marginal impacts for climate (usually temperature and rainfall) (Kurukulasuriya et al., 2006; Lippert et al., 2009), which can be used for an analysis of variability. This approach has also been used to analyse how some socioeconomic variables influence the sensitivity of agriculture to climate change (see, e.g., Mendelsohn et al., 2001, with variables related to country development).

In order to assess national effects, weighing techniques are used. These include percentage of cropland, weights based on crop revenue (Mendelsohn et al., 1994, 1996) or predicted variance (Mendelsohn et al., 1996). The influence of adjacent administrative

Table 4.4 Summary of the characteristics of Ricardian approach

Farm-level assessment	Observations	References
Economic farm performance and farm value	Farm land value and farm revenue	Mendelsohn et al. (1994, 1996) Kurukulasuriya et al. (2006); Mendelsohn and Reinsborough (2007) Deressa (2007) Lippert et al. (2009)
Regional and global assessment		
Sectorial economic effects	By changes in aggregated farm value using different weighing techniques.	Mendelsohn et al. (1994); Lippert et al. (2009); Kurukulasuriya et al. (2006)

units has also been considered (Lippert et al., 2009). Finally, Polsky and Easterling (2001) integrated regional average measures in a multi-level analysis that considers influence of some variables at different spatial scales.

One of the strengths of this approach is that it implicitly incorporates adaptation (Polsky and Easterling, 2001; Kurukulasuriya et al., 2006). However, they cannot be applied under different policy scenarios and it is also impossible to test different adaptation options. The limits of the approach have been widely discussed (see, e.g., Darwin, 1999; Darwin, 2004).

Another advantage is that it uses monthly average data from global or regional climate models, thus avoiding the uncertainties related to daily data estimation needed by other tools (e.g. process-based models). The Ricardian approach has been widely used when actual economic data are available, because it is easy to apply and is statistically significant. However, the same discussion about the limits of statistical relationships between temperature and (in this case) economic performance of the production function can be applied.

These correlations are used to predict future values when climate change scenarios are used as climate input. However, CO₂ fertilization is not considered because the statistical correlation is built under present atmospheric concentrations.

This approach has also been criticized for not considering changes in prices as a consequence of modifications in regional or global demand and supply equilibrium, and because the implicit assumptions of considering adaptation cost can always be assumed by farmers (Darwin, 2004). It has been argued that the hedonic approach cannot be used to estimate dynamic adjustment costs (Darwin, 2004). This limits their use for long-term scenarios where changes in socioeconomic drivers can produce deep sectoral restructuring. Another problem of this technique is the difficulty of comparing results between assessments that use different independent variables. Table 4.4 summarizes the characteristics of the Ricardian approach.

Microeconomic Modelling

In some infrequent cases economic models have been used to calculate economic performance at the farm-level. In this case, yields from process-based models are used as

an input to farm-level economic models. An example can be found in Gibbons and Ramsden (2005). They use Farm-adapt, an economic mixed-integer programming (MIP) model that maximizes farm net margin to assess economic impacts of climate change at the farm level.

This approach has the advantage of providing a better analysis of management options so that different adaptation scenarios can be compared. The main problem associated with this assessment is related to the calculation of future prices for inputs and outputs. For example, negative correlations between yields and prices are not considered (Gibbons and Ramsden, 2005). As an alternative, future prices can be used from macro-economic modelling to evaluate local economic effects and future management options.

Macroeconomic Modelling

As the importance of global markets became increasingly recognized as a key factor for assessing climate change impacts, much research combined tools to estimate changes in crop yields with macroeconomic simulations so as to obtain better assessments of economic effects.

With this objective, computable general equilibrium (CGE) Models have been used to predict the economic effects of climate change. Ciscar et al. (2011) used a basic linked system to analyse economic effects of yield changes calculated through DSSAT crop models (Parry et al., 2004). More recently the Global Trade Analysis Project (GTAP) (Hertel, 1997) has been used for the same purpose to analyse economic effects in Europe (Quiroga and Iglesias, 2009) and other countries (Ciscar et al., 2011). In these cases, economic models do not incorporate climatic relationships. Therefore climate scenarios are introduced as new computed yields for each economic unit usually countries (Parry et al., 2004).

Ciscar et al. (2011) and Parry et al. (2004) used agro-ecological zone (AEZ) yield and land-use data as an input for the World Bank's LINKAGE model calibrated with GTAP in an estimation of economic effects in China. Recently GTAP also has been coupled with land-use model KLUM to estimate global changes in cropland patterns (Ronneberger et al., 2009).

The second objective of this approach is to assess global production in order to analyse food security (Parry et al., 2004). The use of macroeconomic modelling implies some grouping actions, such as combining countries into regions and grouping economic sectors outside agriculture. The different approaches used difficult comparative analysis. Other problems with these techniques is related to the assumptions of different stages (i.e. process-based crop models and macroeconomic models) that can be significantly different. The interdependence of inputs and outcomes in macroeconomic modelling on a year-by-year basis can also be discussed. In this sense, recent studies show that results can be significantly different when models are coupled (Ronneberger et al., 2009). Therefore there are increasing calls for new model development involving several groups of tools (Easterling et al., 2003; Challinor et al., 2009). Table 4.5 summarizes some of the characteristics of the macroeconomic modelling approach.

Table 4.5 Summary of the characteristics of the macroeconomic modelling approach

Regional and global assessment	Observations	References
Regional and global productions and food security	Coupling GTAP model with land-use model	Parry et al. (2004); Parry (2007); Iglesias and Rosenzweig (2009); Ronneberger et al (2009)
Sectorial economic effects		Quiroga and Iglesias (2009); Zhai et al. (2009)

Summary

The models and tools discussed in this section, including agroclimatic indices, process-based models, production functions, the Ricardian approach and the economic approaches, are summarized in Table 4.6, along with their relevant strengths and weaknesses.

SPATIAL SCALES, UNCERTAINTY AND CLIMATE VARIABILITY WITH CLIMATE IMPACT ASSESSMENT

In this section we discuss methods used to aggregate site-level estimations that deal with the spatial variation of biophysical conditions for crop production, site crop management and spatial influence of socioeconomic drivers, including the whole set of policies affecting crop production.

Since crop models are data intensive they are typically validated at site level so that all key variables can be controlled. However, global and regional estimations of crop productivity and production require the spatial aggregation of discrete data in order to obtain regional and global predictions of climate change impacts. Different approaches to spatial aggregation are used depending on the variables considered and on the availability of data. From the spatial point of view, they can be grouped according to the type of spatial unit used and whether the scaling method is applied to inputs, outcomes or both.

One common approach is to use gridded areas (spatial units with the same area and shape) where every grid unit is represented by individual values for the involved variables. This approach requires continuous spatial data for each variable and input data with the same resolution. If low resolution is used, one cell is a heterogeneous unit represented by the average or the most frequent value of the variable. However, gridded calculation of variables may create a scaling-down problem of spatial variables with low resolution. This is the case for climate change scenarios where the size of the cell analysed influences the results. For example, Adams et al. (2003) found differences in the economic behaviour of the agricultural sector when they used data from global models (CSIRO CGM with 5-degree cell, about 400 km) and when they used regional models resulting from a downscaling process (RegCM with 50 km cell).

Gridded coverages can be derived from discrete site information using spatial interpolation methods like weighting, splining or kriging (for a detailed revision of spatial interpolation methods see Lam, 1983; Li and Heap, 2008). An easier option is to use gridded

Table 4.6 Summary of the characteristics of the models that estimate crop productivity

Type of model	Description and use	Analytical level	Strengths	Weaknesses
Agroclimatic indices	Based on combinations of climate factors important for crops. Used in many agricultural planning studies. Useful for general audiences and for quick assessment	Oriented to estimate productive potential or potential distribution of crops	Simple calculation. Effective for comparing across regions or crops	Climate based only, lack of management responses or consideration of carbon fertilization or climatic variability
Process-based crop models	Calculate crop responses to factors that affect growth and yield (i.e. climate, soils and management). Used by many agricultural scientists for R&D	Used to calculate crop yields. Used to simulate management scenarios	Process based, widely calibrated and validated. Useful for testing a broad range of adaptations. Test mitigation and adaptation strategies simultaneously. Available for most major crops	Require detailed weather and management data for best results. When they are used alone they don't consider economic profit as a determinant of crop selection
Production functions	Based on the empirical relationship between observed climate and crop responses. Used in yield prediction for famine early warning and commodity markets	Used to calculate yields. Used to scale up outcomes of process-based models	Present-day crop and climatic variations are well described and the response to future climate may be introduced when deriving yields with process-based models	Require time series of data; require empirical and process based yields for best results. Limited management options (e.g. only crop selection instead of cultivars selection) if they are used alone
Ricardian approach	Statistical relationships between land value and climatic variables	Used to calculate effects of climate change on land prices	Easiest way to estimate economic effects of climate change on farm land	No significant changes on markets; prizes of crop productions or demand are considered. Require data about land prices

Table 4.6 (continued)

Type of model	Description and use	Analytical level	Strengths	Weaknesses
Economic models	Models used to estimate economic functioning of agricultural sector under current and future conditions	Used to calculate economic performance of agricultural sector and, as a result of equilibrium between supply and demand, to estimate global and regional productions	Consideration of all major variables concerning agriculture sector and global food system including trade balances and relationships with input prices. Can be related with socioeconomic scenarios	Statistical relationships are site specific because national markets may work differently Assume that supply always cover demands. Limited consideration of adaptation strategies if they aren't introduced as changes in yields. Needs spatial aggregation of local yield data because usually national average data are needed as an input. Difficult to downscale to identify local or specific impacts (e.g. with small farmers)

data to calculate new climate distributions or agroclimatic indices under future climate change conditions (e.g. Kottek et al., 2006). This approach was used to obtain the first estimations of climate change impacts on crop productions (e.g. Rosenzweig, 1985). This approach is also used to apply a production function model to calculate crop yields for all the points in a grid (Carter and Saarikko, 1996). In this case, an additional problem arises regarding how to integrate model software and GIS. One option is to embed GIS functionality into crop model software, another is to embed the crop model into GIS software, and yet another includes the use of loose or tight coupling (for a detailed description see Sui, 1998). Data for spatial grids can also be obtained from remote-sensing data. Specific methods have been developed to obtain climate data (see, e.g., Mearns et al., 2003) and crop yield estimation (Shanahan et al., 2001; Baez-González et al., 2002; Lobell and Asner, 2003; Lobell and Field, 2007; Reidsma et al., 2010).

Another group of techniques to aggregate spatial data is homogeneous areas. These are irregular areas defined by a common value for one variable or for a narrow set of selected variables. In continuous variables, single values can be replaced by value ranges. Homogeneous areas can be derived through interpolation from discrete sites where models are calculated, tested or calibrated. These areas represent the site, so this kind of method can be used as a spatial classification technique. Another approach is used when

several sites fall in the same area in order to collect their internal variability. In this case a crop function can be derived for every unit.

Often homogeneous areas are defined using the same variables of crop model, although it is more frequent to expand this set to include a multicriteria approach, as when using agro-ecological zones (Fischer et al., 2005). In these cases, climatic variables are assembled together with soil, slope, land use/cover, vegetation and others to define homogeneous agro-ecological areas. Crop management, technology and other socioeconomic determinants of crop productivity are integrated through land utilization types (LUT), which are based on land-use data. A similar approach based on climatic data and crop management practices is used by Iglesias et al. (2000) and Parry et al. (2004).

The possibility of integrating biophysical variables with socioeconomic aspects is a major advantage of this approach. It is critical to include farmer practices because crop management accounts for 50 per cent of yield variations (Lobell and Field, 2007). They can also be easily understood by stakeholders and decision makers because homogeneous areas represent current management practices. The spatial and scale problem is one of the key dimensions of the potential problem of discrepancies between scientific evaluator's and policy makers' points of view (Cash and Moser, 2000). Although there is some controversy regarding the process for selecting strategic variables due to concerns over subjectivity when correlation methods are not used (i.e., against statistical data about crop productions or land use), future scenarios can be related to current spatial variability to facilitate the process of developing or discussing adaptation strategies and scenarios.

Another option is to derive average data for administrative units. This has been used for climate data. Mendelsohn et al. (1994), for example, aggregated meteorological data to calculate county average climates for 3000 US counties. However, computational advances and data availability allow better options to keep the spatial variability of biophysical phenomena based on geostatistical methods. Even with low resolution, spatial aggregation is a source of uncertainty when units have great variability, for example mountainous countries (Lobell and Ortiz-Monasterio, 2006). However, aggregation of crop productivity by administrative units is needed to integrate changes in crop yield under climate change scenarios into economic models to estimate monetary effects of climate change (e.g. Mendelsohn et al., 1994; Quiroga and Iglesias, 2009; Parry et al., 2004; Adams et al., 2003) and to simulate policy scenarios.

The scaling-up process has been discussed in some papers (e.g. Mendelsohn et al., 1994; Hoogenboom, 2000; Polsky and Easterling, 2001; Adams et al., 2003). These papers noted several problems. The first is specific to extrapolation processes of site-based analysis (e.g. with process-based crop models). The representativeness of site locations must be carefully examined when there is both spatial and temporal variability of data. In these cases there is a strong risk of overestimating variability (Hoogenboom, 2000), and several statistical techniques are proposed to solve this issue (see Hoogenboom, 2000). Other problems are related to the weighted aggregation of economic assessments in Ricardian approaches. Some techniques have been tested, including multi-level approaches, to introduce the influence of different levels of administrative units into the analysis (Mendelsohn, 1994; Polsky and Easterling, 2001). Finally the third common problem is related to the selection of an appropriate working scale. The selected option affects results and comparative work has been done in order to analyse causes and effects of these differences (see, e.g., Challinor et al., 2003; Adams et al., 2003).

UNCERTAINTY IN PROJECTIONS OF CROP PRODUCTION

Uncertainty in projections of crop production is derived from a vast array of sources including uncertainties regarding climate change predictions, technological developments and socioeconomic factors (Iglesias et al., 2011). Uncertainty about the future always depends on the assumptions being made; for instance, some assumptions are more certain at the global scale (e.g. population increase, technological trends), while others are more certain at the regional or local scale (e.g. environmental policy trends in the richer countries) (Iglesias et al., 2007; Ciscar et al., 2011). Additionally, efforts to deal with these uncertainties may in turn create more sources of uncertainty. For example, in downscaling, uncertainty increases from global to local climate impacts (Giorgi and Lionello, 2008; Lloyd-Hughes and Saunders, 2002).

Here we describe sources of uncertainty in crop models and climate scenarios, and then discuss methods that have been utilized for estimating these uncertainties in recent research.

Sources of Uncertainty in Crop Production Models

The crop productivity models contain many simple, empirically derived relationships that do not completely represent actual plant processes. When models are adequately tested against observed data (calibration and validation process), the results represent agricultural output under current climate conditions. Nevertheless, the simplifications contained in crop models are a source of uncertainty for the results. For example, crop models in general assume that weeds, diseases and insect pests are controlled, no problems in soil conditions such as high salinity or acidity exist and that there are no catastrophic weather events such as heavy storms. Although the crop models simulate the current range of agricultural technologies available around the world and do not include potential improvements in technology, they may be used to test the effects of some potential improvements, such as improved crop varieties and irrigation schedules.

Provided that the limitations are carefully evaluated, a range of models is used by scientists, technical extension services, commercial farmers and resource managers to evaluate agricultural alternatives in a given location under different conditions (i.e. drought years, changes in policy for application of agro chemicals, changes in water input, among others). The demand and resource use adjustments simulated by social science models incorporate further assumptions and increase the uncertainty of the results. The general equilibrium economic models also include functions that describe the non-agricultural sector. Because of many uncertainties, quantitative estimates of agriculturally related economic impacts of greenhouse gas emissions are often given low confidence. A major source of uncertainty is our inability to accurately project future changes in economic activity, emissions and climate. Finally, scaling up the model results to a regional level is, as in most scaling exercises, not an easy task and one that always increases the uncertainty of the evaluation. Scaling up is, however, of crucial importance for regional and international policy.

Table 4.7 Characterization of agronomic impacts, adaptive capacity and sector outcomes

Biophysical impact	Expected intensity of negative effects	Secondary impacts	Adaptive capacity	Uncertainty level
Changes in crop growth conditions	High for some crops and regions	Changes in optimal farming systems. Relocation of farm processing industry	Moderate to high	Medium
Changes in precipitation and the availability of water resources	High for developing countries	Increased demand for irrigation. Reduced yield of crops. Increased water shortage	Moderate	Medium to low
Changes in agricultural pests	Medium	Pollution by increased use of pesticides. Reduced yield and quality of crops	Moderate to high	High to very high
Changes in soil fertility and erosion	High for developing countries	Biodiversity loss. Decreased yield of crops. Increased risk of desertification	Moderate	Medium

Sources of Uncertainty in Climate Scenarios

The uncertainty derived from climate models is related to the limitations of current models in representing all of the atmospheric processes and interactions of the climate system. Regional climates naturally fluctuate about the long-term mean. For example, rainfall variability occurs in terms of timing and quantity, and affects agricultural production each year. It is clear that changes have occurred in the past and will continue to occur, and climate change modifies these variability patterns, resulting in more droughts and floods, for example. Nevertheless, predictions, especially regarding rainfall scenarios, are very uncertain. The limitation of projecting the socioeconomic development pathways is an additional source of uncertainty. Climate change, population dynamics and economic development will probably affect the future availability of water resources for agriculture differently in different regions.

Estimating Uncertainty in Impact Assessment

For a particular evaluation of impacts, the sources of uncertainty discussed above may vary considerably. For example, an attempt to reduce uncertainty by using multiple scenarios may imply having to choose simpler models for impact assessment, which in turn produces more uncertain results. It is therefore difficult to determine the level of uncertainty present in an impact assessment.

The uncertainty level associated with the impacts that climate change will have on food production as identified by using the tools and models available is outlined in Table 4.7. Although considering all factors that determine uncertainty presents difficulties, we can draw conclusions for different geographical units of analysis. The

level of uncertainty along with the net impact decreases as the geographical scale increases.

The inclusion of uncertainty (i.e. when the event is known but the probabilities that it will occur are not known) in assessments of climate change impacts is very important for reducing and evaluating risk; unsurprisingly, recent studies are now beginning to include explicit methods to deal with these sources of uncertainty. While earlier studies often used best-estimate scenarios to represent the mid-point of predictions, recent work has included a range of scenarios that represent the upper and lower bounds of the predicted effects in a more realistic manner, thus reducing levels of uncertainty throughout the model system. Additionally, the probability distributions of different events may be defined, while differentiating between low-probability catastrophic events and higher-probability gradual changes in climate trends. Another recent approach has been to use Monte Carlo simulations to test the sensibility of results and to explore the consequences of data variability (Lobell et al., 2008; Iglesias and Quiroga, 2007).

A common approach to reducing uncertainty in climate change impact assessment is to use of a range of scenarios to project future conditions. In this case several works point out the need for better predictions of future rainfall (Lobell et al., 2008, among others).

AN OVERVIEW OF CLIMATE VARIABILITY

Changes in climate variability, including the frequency and severity of extreme events such as droughts and floods (IPCC, 2007), will directly affect crop production. Numerous studies have concluded that changes in climate variability and extremes will have a greater impact on crop production than changes in average climatic conditions (Katz and Brown, 1992; Porter and Semenov, 2005). As a result, climate variability is a decisive factor when considering climate change impacts on agriculture (Mearns et al., 1997, Meinke and Stone, 2005). Recent scholarly work has generally dealt with variability in two ways. The first has been to measure the amount of risk for crop production that is a corollary of climate variability, and the second has been to stress the importance of climate forecasts and their relevance for agricultural performance.

Estimating Risk

In terms of agricultural production, variability increases risk for farmers whose harvests may be lost due to unpredictable climate conditions.

EL Niño–Southern Oscillation (ENSO)-related variability has been extensively studied because of its impact on crop production, food security and the frequency and intensity of extreme events. For the case of ENSO-related climate variability in Argentina, Ferreyra et al. (2001) developed a linked-modelling framework to estimate maize production risk. In their paper they link climatic, agronomic and economic components into a framework with which they compute risk curves based on a comparison of the likelihood of exceeding a given yield or income during a scenario compared to the same likelihood in a reference scenario.

Iglesias and Quiroga (2007) use a different methodology for measuring the risk of climate variability to agriculture in Spain. Their methodology comprises three steps; the first is the utilization of multiple linear regression models to estimate the risk of climate variability; the second uses Monte Carlo models to perform a detailed analysis of the probabilistic properties of agricultural yields, and the third applies a risk factor index to compare the risk of low yields due to climatic factors.

Forecasts

The importance of forecasts is intricately linked to risk reduction for farmers whose ability to foresee future climate will directly impact their management decisions. Relevant forecasting results can help farmers adapt to an increasing climatic variability by reducing their risk exposure and risk aversion through allowing them to make more informed decisions and through the development of insurance schemes (Iglesias et al., 2009). Given the myriad of factors that forecasts must take into account, the task of creating reliable and valuable forecasts requires researchers to make assumptions about the climate system, the agricultural system and decisions likely to be made.

The main basis for seasonal forecasting is the premise that lower-boundary forcing (including considerations of sea surface temperature, sea-ice cover and temperature, land-surface temperature and albedo, soil moisture and snow cover) can help predict atmospheric developments (Sivakumar and Hansen, 2007). Forecasts are produced through mathematical models of the climate system. These tend to employ operational empirical–statistical methods that are based on statistical links between current observations and future projections of weather conditions. Alternatively, dynamic model-based methods use atmospheric GCMs or coupled atmosphere–ocean GCMs to predict the evolution of the global climate system in response to initial atmospheric conditions (Sivakumar and Hansen, 2007). Evidently these models and methods must deal with considerable levels of uncertainty due to their probabilistic characteristics. Sivakumar and Hansen (2007) believe that the quality of forecasts will improve in the coming years thanks to the use of coupled crop models within climate models and the extension of remote sensing and spatial environmental databases that provide improved data.

Until recently, the use of dynamic climate models to simulate crop performance was complicated by differences in spatial and temporal scales between GCMs and crop models and the non-linear relationships between meteorological variables and crop responses (Hansen et al., 2006). Recent methodological developments have however emerged to bridge the differences between climate models and crop simulations. Hansen et al. (2006) summarize a number of these methodologies, including the development of crop simulations through the use of daily climate model outputs (as in the case of Mavromatis and Jones, 1998, who used daily outputs from the HadCM2 GCM as input for the CERES-Wheat model); the creation of synthetic daily time series that are disaggregated from seasonal climate forecasts (as in Mearns et al., 1997); and the statistical prediction of simulated crop response based on the use of yields simulated with historic daily weather data to condition crop model output (as in Hansen and Indeje, 2004, who used this method to predict simulated maize yields in Kenya).

CONCLUSION

Crop production demand will increase, and droughts and floods will be more frequent and extreme, making crop production more vulnerable. Understanding the uncertainty of crop production estimates is crucial for increasing adaptive capacity to climate change. Studies completed to date concur that there will be significant changes in global crop production patterns. All regions are likely to be affected, but large differences will occur over different regions. While the combined changes in global production due to climate change may be small, the potential remains for regional vulnerability to food deficits due to problems of ensuring adequate food distribution to specific regions and groups of people. For subsistence farmers and people lacking entitlement to food, lower productivity may result not only in measurable economic losses, but possibly malnutrition and starvation.

Although different analytical methods for evaluating crop production may be used depending on the objective of the study, agronomic studies can best be achieved through the use of production functions that link climate, management and environmental variables to crop production. Nevertheless, each method for evaluating crop production provides information on different types of impacts. For example, simple agroclimatic indices can be used to analyse large-area shifts of cropping zones, while process-based crop growth models should be used to analyse changes in crop yields.

Several existing tools can be applied for a regional evaluation, and the results may be visualized in the form of maps. This regional approach is essential for integrating climate change, crop production, water demand indices and socioeconomic indices, thus providing a first-order evaluation tool for analysing possible adaptation strategies. A local approach involves local studies that analyse the sensitivity of crop yield, farm management and water use to climate at the local scale, and the implications for policy decisions that affect water management policies. Crop models typically focus on optimizing the timing of the production and the efficient use of nutrients (primarily nitrogen) and irrigation water. Since economic sectors vary greatly among different countries and physical environments, different methods of impact assessment will be appropriate. It is likely that a mix of approaches will lead to the most robust set of results for a given area.

The major challenge facing all crop production evaluations is the incorporation of qualitative changes deriving from complex interactions (e.g. production, water availability and rural development). Effects on income, livelihoods, and employment can only be assessed using economic and social forms of analysis (Ciscar et al., 2011). An advantage of using general equilibrium models for this type of analysis is that the linkages between population increase and food production can be explored.

Policy responses to the agricultural production implications of climate change will have to be formulated in conditions of uncertainty, which will exist regarding the scale and timing of the effects as well as their nature, location and intensity. Key challenges include the reduction of social vulnerability and the improvement of science to support adaptive responses. Uncertainty about the future calls for public engagement about scientific findings and communication with responsibility and care. Uncertainty about predictions, however, is not an excuse for inaction.

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5 Investigating the connections between climate change, drought and agricultural production

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INTRODUCTION

The 2008 global food security crisis and the 2010 drought and heat wave in Russia's wheat belt are two recent examples of how the challenges of poverty, equity, food security, water availability and climatic variability are already affecting agricultural systems around the world. In the developing world where food can easily consume more than 50 per cent of family incomes, any event negatively affecting agricultural systems has major ramifications (FAO, 2010). Within that context, the Food and Agriculture Organization (FAO, 2009) of the United Nations has identified climate change as an additional challenge facing agriculture, forestry, fisheries and food security in the future. The simultaneous evolution of climate change impacts combined with global population growth estimated to reach 9.1 billion in 2050 illustrates that in order to continue to provide food, feed, fiber, employment, income and ecosystem services for the world, agricultural systems are going to have to incorporate climate change adaptations into efforts to address the growing demands associated with more people (FAO, 2009).

Agricultural production and its annual variability are affected by the weather as well as factors of climate such as temperature, precipitation, carbon dioxide concentrations and water availability. These factors also affect the insects, diseases, weeds and soils that in turn influence agricultural production (Hillel and Rosenzweig, 2009; Backlund et al., 2008). Climate and climatic variability, therefore, play a major role in defining agricultural production around the world. The most pertinent climatic characteristics are annual temperature and precipitation. However, features of climate that focus on the seasonal distributions of these two indicators and capture their characteristics as a function of growing-season length, maximum and minimum temperatures and evapotranspiration are also important in defining agricultural production in any particular region. Additional features such as soil moisture, soil temperature, wind speed and relative humidity can also influence agriculture. It is the variability of each of these climatic characteristics as well as their increasing potential for change that pose a threat to agricultural systems in both the short and long run.

The nature of climate change impacts and climatic variability on agricultural systems around the globe is complicated by the regional nature of temperature and precipitation shifts, and by an anticipated increase in some of the extreme weather events affecting agricultural production (Karl et al., 2008). One extreme weather event is drought. Droughts, as illustrated by the 2010 drought and heat wave in Russia, are current agricultural challenges and are the major cause of agricultural losses in many developed nations. Droughts can also trigger famine and human mortality in the developing nations (see

the EM-DAT database put together by the Centre for Research on the Epidemiology of Disasters for drought disaster profiles of these nations [<http://www.emdat.be/database>]). As officials struggle to understand the impacts of drought resulting from natural climatic variability, the current state of the science indicates that with climate change, droughts may increase in both frequency and intensity in the future (Kundzewicz et al., 2007; Meehl et al., 2007).

This chapter contributes to the present volume by providing a perspective on drought as a natural hazard followed by an examination of the relationships between drought, climate change and agriculture. A growing volume of recent literature and research illustrates the complexities of these relationships, and the chapter ends with a case study highlighting some of the research on this topic taking place in Europe.

DROUGHT AS A NATURAL HAZARD

Drought is a natural hazard that occurs in almost any location in the world. Former Secretary-General of the World Meteorological Organization, Godwin Olu Patrick Obasi, claimed that drought affects more people than any other hazard (Obasi, 1994). Drought has unique characteristics that make it quite different from other natural hazards. Droughts have long been described as ‘creeping phenomena’ that often develop slowly; it can be months or years before officials even realize they are in a drought situation (Gillette, 1950). This is very different from other hazards such as tornadoes, floods, earthquakes or tropical storms. A second characteristic of droughts, articulately stated by Tannehill (1947), is that they lack a clear, quantitative definition. Other hazards are defined by various parameters such as flood stages, the Fujita Scale for tornadoes, the Richter Scale for earthquakes or the Saffir–Simpson Scale for hurricanes. Uncertainty about what a drought is, whether a drought is occurring or not and its severity leads to confusion and inaction by officials in responding to drought events (Yevjevich, 1967; Glantz and Katz, 1977). Finally, a third unique characteristic of droughts is that they lack the dramatic visual impacts that are so common with the other hazards, allowing drought events to escape the attention of officials, the media and the public until the event is especially severe (Wilhite and Buchanan-Smith, 2005).

Given the characteristics of drought and its complex nature, it can be beneficial to identify drought types from various disciplinary perspectives. Wilhite and Glantz (1985) identified four perspectives: meteorological, agricultural, hydrological and socioeconomic. A meteorological perspective focuses on the degree of severity of precipitation deficits using a variety of indicators and indices that have been developed to highlight these deficits. Agricultural drought involves the relationship between plant water demands and the amount of available water, particularly within the soil environment. This perspective of drought is most relevant for the discussions in this chapter. A hydrological perspective deals with the longer-term nature of the relationship between precipitation deficits and the hydrological resources in a region such as streamflows, reservoir levels, snowpack and groundwater. Because irrigation can depend on the hydrological resources of a region, agricultural production can be affected by a hydrological drought. Socioeconomic droughts are related to the various impacts affecting society and the environment as a result of the meteorological, agricultural or hydro-

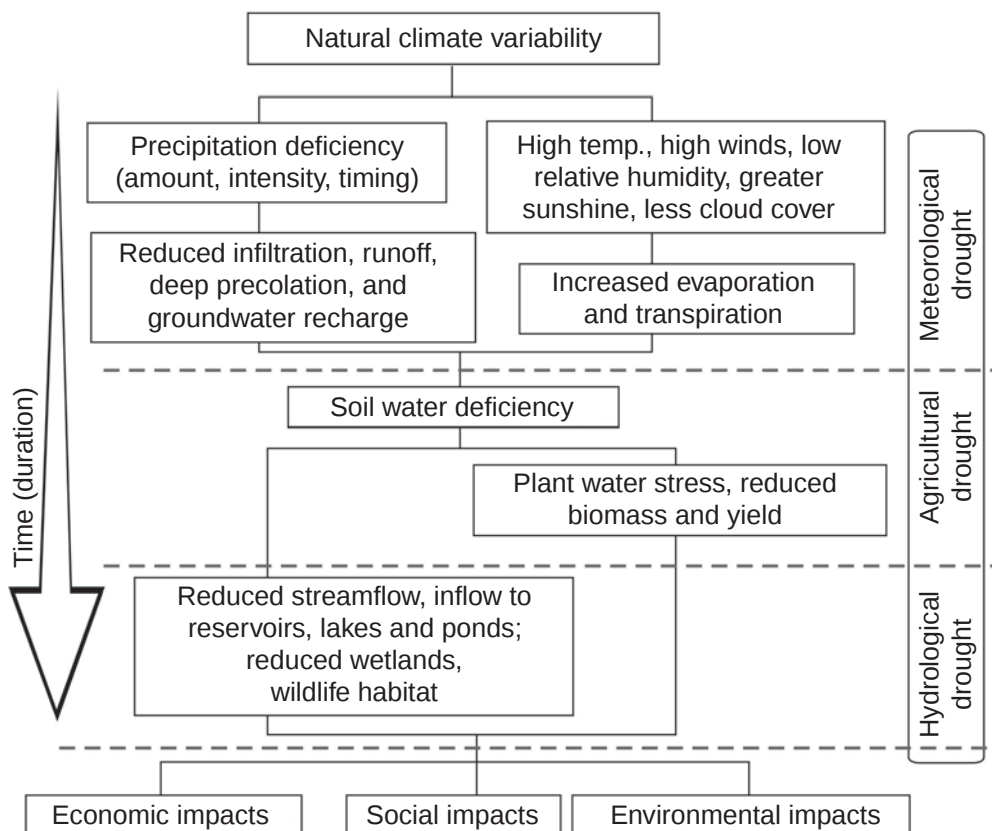


Figure 5.1 The disciplinary aspects of drought

logical droughts. The distinction between these four perspectives is often blurred and interrelated, although a time element component does tend to be involved with each perspective (Figure 5.1).

Within the USA droughts are one of the most costly of all natural hazards. An estimate by the Federal Emergency Management Agency (FEMA) calculated annual drought losses for the nation at US\$6–8 billion per year (FEMA, 1995). Because of the unique and complex characteristics of drought, it is difficult to systematically assess economic losses at the national scale. However, NOAA's National Climatic Data Center (2010) has estimated that the 1988 drought resulted in losses of US\$71.2 billion (in 2007 dollars). They also reported 14 drought/heat wave events since 1980 totaling more than US\$180 billion, which represents 25 per cent of all losses from billion-dollar weather disasters. The average loss per disaster for droughts and hurricanes (about US\$13 billion per event) is far higher than the average for any other weather disaster (NCDC, 2010).

Drought impacts are becoming more complex as the demand for water grows and the value that societies place on interests such as recreation and environmental issues increases. In the USA, for example, drought used to be considered a hazard that mainly affected agriculture. Recent droughts across the country have shown that this is no

longer true. Agricultural impacts are still major, but so are the impacts on energy production, transportation, tourism and recreation, forest and wildland fires, urban water supplies, environment and human health. Conflicts between water users are also increasing and droughts exacerbate these issues (GSA, 2007). It is also important to note that because of the different vulnerabilities around the world, the impacts of drought on vulnerable populations or environments will vary. Some of the factors influencing the nature of drought impacts include poverty levels, urbanization, population densities and land-use practices.

Historically, most of the emphasis focusing on drought impacts has had to deal with responding to these impacts after an event. This has been true in the agricultural sector as well as in the other sectors affected by droughts. Not surprisingly, given the characteristics of drought, responses have often been uncoordinated and untimely (GSA, 2007; Wilhite and Pulwarty, 2005). Little attention has been placed on trying to reduce future impacts resulting from drought events by improving drought monitoring, planning and mitigation strategies (Wilhite et al., 2005). This approach, often called drought risk management, requires a new paradigm for how to prepare for future droughts. Drought risk management is proactive and directed at identifying who and what is at risk, why they are at risk and how individuals respond to events. Drought plans can be adopted and mitigation strategies and programs can be identified in those sectors, population groups or geographic regions at risk. The recommendations of the National Drought Policy Commission's report to the US Congress (NDPC, 2000) emphasized that an approach focusing on risk management, preparedness and mitigation, including a more comprehensive drought monitoring system, be adopted within the USA. Although the progress has been slow, there has been some success in moving forward with drought risk management around the world (Wilhite et al., 2005).

DROUGHT AND AGRICULTURE

Although many sectors experience drought impacts, the agricultural sector may be the most vulnerable sector to drought events worldwide. A conceptual definition for agricultural drought is a deficiency of precipitation in combination with high temperatures and other factors that, when extended over a period of time, results in soil moisture deficiency, plant water stress and reduced crop yields (Wilhite and Buchanan-Smith, 2005). Trnka et al. (2010) point out that agricultural production is especially vulnerable to heat and water stress during the critical crop development stages. In addition to the effects of reduced crop yields, droughts increase the potential for pest infestations, weeds and diseases, which work to reduce crop quality as well as crop quantity (GSA, 2007). Droughts also affect soils and soil function, and play a part in desertification, each having an impact on agricultural production (Hillel and Rosenzweig, 2009; Fischlin et al., 2007). Agricultural livestock production is affected by droughts as the quantity and quality of available forage on rangelands and pastures is reduced (GSA, 2007). In fact, all agricultural producers face indirect impacts during droughts that can range from increased water and energy costs for irrigation to the economic impact on communities as the agricultural productivity within a region is diminished.

A few examples of how drought affects the agricultural sector are provided. Within the USA one potential measurement of the impacts for agriculture can be seen in the crop indemnity payments made as part of the national crop insurance program (Figure 5.2 – see p. 246). Between 1989 and 2008, more than US\$17 billion of indemnities have been paid out for drought-related losses, or about US\$1 billion per year and 38 per cent of all indemnities paid. These amounts are not large when compared to the US economy as a whole, but they illustrate how drought can have devastating regional and local impacts.

During the 2002 drought in the USA, the National Drought Mitigation Center began to collect economic loss information from a variety of sources. Although multiple sectors were affected, losses within the agricultural sector were the most commonly documented. Even the agricultural loss information available, however, was incomplete, and different methodologies were used to determine the loss information in each case. One study of the agricultural losses in South Dakota during 2002 used an input–output model to estimate the direct drought impacts on crop and livestock production, as well as the secondary effects on the state’s economy (Diersen et al., 2002). Their original estimate of US\$1.8 billion was revised later to US\$1.4 billion when improved market conditions and direct federal aid of US\$100 million to the state were considered (Diersen and Taylor, 2003). A more recent report highlighted that the 2008–09 drought in the San Joaquin Valley in California resulted in an estimated 16 200 to 23 700 jobs lost and between US\$440 and US\$644 million losses due to reduced crop production and related business (Drought Operations Center, 2009). The report included direct and indirect impacts but did not include losses to dryland range and pasture, non-irrigated crops, livestock operations or dairies.

These examples illustrate the complexity of drought impacts on the agricultural sector. In one attempt to understand some of this complexity, the National Integrated Drought Information System (NIDIS), created in 2006 to improve coordination of the USA’s drought early-warning capabilities, has established a pilot project covering the Apalachicola–Chattahoochee–Flint (ACF) River Basin in the southeastern USA. Figure 5.3 (see p. 247) is a map of the basin, with four sub-basins identified along with the sectors that will be examined in each particular sub-basin. Although the agricultural sector is identified as being the primary sector for the Flint River Basin, the figure illustrates how interconnected all the sectors are. The objective of this and the other two pilots is to prototype and develop frameworks for drought early-warning systems (DEWS) for the USA. These pilots are to explore and demonstrate a variety of early warning and drought risk reduction strategies that incorporate drought monitoring and prediction information in partnership with users and federal, state, regional, tribal and local agencies (NIDIS: <http://drought.gov/portal/server.pt/community/acfrb>). NIDIS has already established a pilot in the Upper Colorado River Basin and is developing a pilot project focused on California as well.

In Europe, recent regional drought events in 1989–91, 2003 and 2006 (in Spain), as well as the 2010 drought in Russia, have highlighted the vulnerability to drought across the continent. In these events high temperatures in combination with diminished rainfall made a huge impact. Some of the impacts recorded during the 2003 drought included a 36 per cent maize yield reduction in Italy’s Po Valley; approximately 30 per cent reductions in France’s maize, fruit and forage productions; and the lowest wine production across the continent in ten years (Easterling et al., 2007). Overall, the uninsured losses in

the agricultural sector for EU countries in 2003 were estimated at €13 billion (approximate US\$16 billion) (Easterling et al., 2007). The impact of the summer 2003 heat wave and drought on agriculture and forestry caused €4–5 billion losses in Italy, €1.5 billion in Germany and €4 billion in France. A drought in Spain beginning in 2005 caused losses of more than €1.6 billion in crop and livestock production (Oiles, 2005).

Recent nationwide measurements of drought impacts have also been conducted in Canada and Australia. A study focusing on the agricultural impacts of the 2001 and 2002 droughts estimated the impacts to the regional and national economy of Canada (Kulshreshtha et al., 2003). Primary impacts were estimated for crops, livestock, orchards and vineyards, while secondary impacts were projected using an input–output model. In its entirety, the impact on the gross domestic product (GDP) was estimated at C\$3.65 billion (or US\$2.34 billion) with an estimated loss of 23 777 jobs. In Australia, Horridge et al. (2005) estimated that the 2002–03 droughts caused an overall reduction of Australian GDP by 1.6 per cent, with 1 per cent directly related to the agricultural sector and the remaining 0.6 per cent due to a multiplier effect.

CLIMATE CHANGE, DROUGHT AND AGRICULTURE

Droughts have had a huge impact on societies since the beginning of civilization (Le Treut et al., 2007). To understand the nature of future droughts, it is important to examine recent trends detected in droughts. These trends would probably be related to the nature of both temperature and precipitation. During the twentieth century, global temperatures increased approximately 0.6 °C (Backlund et al., 2008). Similar trends have also occurred across specific regions (Richardson et al., 2009). The trends have been consistently positive for temperature for much of the globe, but precipitation trends are more spatially variable down to small scales and reflect the complexity of the hydrological cycle and efforts to monitor it (Trenberth et al., 2007). For annual precipitation the spatial distributions of trends around the globe are mixed, depending on the location and the time series used. Similar variability exists in trends for seasonal precipitation and monsoon periods, which would have a direct impact on agricultural production.

Dai et al. (2004) investigated global drought trends using the historic Palmer drought severity index. Since 1950, Dai et al. have found increasing drying conditions across most parts of Eurasia, Africa, Canada, Alaska and eastern Australia. They noted that these regions are also associated with stronger surface warming. In Europe specifically, Olesen et al. (2010) summarized several studies that showed more stations in central Europe with statistically significant drier conditions in terms of soil moisture compared with stations that showed no trend or significantly wetter conditions.

Trying to comprehend future drought occurrence also requires an understanding that (1) past climate may not represent the best analog for the future (Milly et al., 2008); (2) recent climate trends do not necessarily reflect future projections; and (3) future drought projections are going to reflect, in part, the projections being made for temperature and precipitation. Temperature projections by Backlund et al. (2008) indicate that global temperatures will increase between 1.1 °C and 5.4 °C by 2100. The projections of precipitation are not as uniform and have higher uncertainty in both spatial and temporal

scales. Other projections that relate to the hydrological cycle include an increase in dry days and an increase in heavy precipitation events (Meehl et al., 2007).

The projections related to drought are an increase in summer droughts and an increase in the frequency of drought events (Meehl et al., 2007; Kundzewicz et al., 2007). Other projections indicate an increase in droughts regionally in the southwestern USA; across parts of Europe and around the Mediterranean region (Kundzewicz et al., 2007; Seager et al., 2007; Olesen et al., 2011; Trnka et al., 2010). The potential impacts on agriculture are substantial. In general, agricultural production could benefit in some cooler regions that experience mild warming and maintain ample growing-season precipitation. However, in many other regions crop and livestock production could be reduced as a result of an increase in heat wave and drought events, as described above. Extreme temperatures are detrimental for either crop or livestock production (Backlund et al., 2008). It is possible, as Trnka et al. (2010) suggest, that yield variability will increase in many regions because of the increased frequencies of both drier and wetter conditions.

In terms of the effect of droughts on agriculture, both rainfed and irrigated agriculture could see impacts on production, particularly because of increased water deficits during summer growing months. Projected reductions in general runoff and runoff generated by snowpack and glaciers could reduce water availability for the agricultural sector in areas where these reductions occur, resulting in greater vulnerability to drought impacts on agriculture (Backlund et al., 2008; Kundzewicz et al., 2007; Meehl et al., 2007). The indirect effect of these impacts would include a decrease in water quality and an increase in salinity for regions dependent upon irrigation. Fischlin et al. (2007) identified some of the potential negative impacts on agriculture: an increase in heat waves and droughts, an increase in wildfires, an increase in desertification across semi-arid regions and new vulnerabilities related to the creation of new combinations of pests, diseases and fire. The overall global impact on agriculture will probably be extremely variable and dependent on factors such as the local environmental and socioeconomic conditions (Eitzinger et al., 2009). The following section presents a case study of research being conducted in Europe on the complex responses of agricultural systems to future climate changes.

A EUROPEAN CASE STUDY

This chapter ends by highlighting some of the current research taking place in Europe by one of the authors (Trnka) in collaboration with a large group of scientists across Europe. The objective of this research focuses on the impacts of climate change on agriculture in Europe, with drought being one emphasis. The context for these research efforts is that temperature projections are consistent in showing increases across the European continent, while precipitation projections are mixed and much less consistent. The discussion below is a synthesis of two articles on the topic (Trnka et al., 2010; Trnka et al., 2011). Please see these articles for more details.

The two Trnka et al. studies (2010, 2011) are unique in that previous studies have either looked at spatial scales that are too large to provide meaningful information for the particular agricultural regions across Europe, or have focused on temporal scales using monthly data for climate- and agricultural-related parameters that do not capture those critical processes taking place during shorter time periods of days and weeks,

Table 5.1 Environmental zones across Europe

Environmental zone (EZ)	EZ acronym	Countries within the EZ
Alpine North	ALN	Finland, Norway, Sweden
Boreal	BOR	Belarus, Estonia, Finland, Latvia, Norway, Russian Federation, Sweden
Nemoral	NEM	Belarus, Estonia, Finland, Latvia, Lithuania, Norway, Poland, Russian Federation, Sweden
Atlantic North	ATN	Denmark, Germany, Great Britain, Ireland, Isle of Man, Netherlands, Norway
Alpine South	ALS	Andorra, Albania, Austria, Bulgaria, Bosnia, Croatia, Czech Republic, France, Germany, Greece, Italy, Macedonia, Montenegro, Poland, Romania, Spain, Slovakia, Slovenia, Switzerland, Ukraine
Continental	CON	Albania, Austria, Bulgaria, Belarus, Belgium, Bosnia, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Moldova, Montenegro, Netherlands, Norway, Poland, Romania, Russian Federation, Sweden, Slovakia, Slovenia, Switzerland, Ukraine
Atlantic Central	ATC	Belgium, France, Germany, Great Britain, Ireland, Luxembourg, Netherlands, Spain, Switzerland
Pannonian	PAN	Austria, Bosnia, Bulgaria, Croatia, Czech Republic, France, Germany, Greece, Hungary, Macedonia, Moldova, Romania, Serbia, Slovakia, Slovenia, Ukraine
Lusitanian	LUS	France, Portugal, Spain
Mediterranean Mountains	MDM	Albania, Bosnia, Bulgaria, Croatia, France, Greece, Hungary, Italy, Macedonia, Montenegro, Portugal, Slovenia, Spain, Switzerland
Mediterranean North	MDN	Albania, Bosnia, Bulgaria, Croatia, France, Greece, Italy, Macedonia, Montenegro, Portugal, Slovenia, Spain, Turkey
Mediterranean South	MDS	Albania, France, Greece, Italy, Malta, Portugal, Spain

which are important for crop development and production. In contrast, the research described within these two articles focused on using daily data to identify the potential weather effects on crop productivity and management for different environmental zones classified by monthly minimum and maximum temperatures, precipitation totals, percentage of sunshine in months representing the four seasons (January, April, July and October) and other physical characteristics such as altitude, slope and the proximity to an ocean or sea (Metzger et al., 2005; Jongman et al., 2006). These zones cover 43 European nations and include the key agricultural regions across Europe, with up to 12 zones investigated depending upon the study (Table 5.1). Although the Continental zone has the largest amount of agricultural land, the Atlantic Central, Pannonian, Atlantic North and Lusitanian zones rank higher in terms of the proportion of land in agricultural production.

For the weather data used in this research, a database of continuous daily weather observations for the 1971–2000 period has been developed for stations across Europe.

The parameters within the database include daily maximum and minimum temperatures, global radiation (or sunshine duration), precipitation, mean daily relative air humidity and wind speed. Agroclimatic parameters were then calculated from the data using a software package called AgriClim (Trnka et al., 2010). The 11 different agroclimatic parameters are related to key agricultural processes representing complex interactions between the climate and crops that occur during a growing season and which affect production. The researchers have focused on parameters that represent extreme events with relevance to agriculture, such as late frost events and drought.

The weather data were used to train a stochastic weather generator, and a 99-year stochastic daily weather series was prepared to represent the baseline (1971–2000) climate conditions at each site (Dubrovsky et al., 2004). The parameters produced by the weather generator were then perturbed using three general circulation models (GCMs) and outputs were created for 2030 and 2050. The three GCMs are from the Hadley Centre in the UK, the Max Planck Institute for Meteorology in Germany and the National Center for Atmospheric Research in the USA, selected because of their ability to accurately reproduce baseline climates across Europe.

Three of the agroclimatic parameters used by the researchers illustrate potential drought-related changes across Europe by 2030 and 2050. The first agroclimatic parameter provides an indicator of potential biomass and crop development. It is the ‘sum of effective global radiation’, which is the sum of global radiation ($\text{MJ}/\text{m}^2/\text{year}$) calculated on days with (1) a daily mean temperature greater than 5°C ; (2) a daily minimum temperature greater than 0°C ; (3) the ratio of actual evapotranspiration (ET) to reference ET greater than 0.4; and (4) no snow cover. When the ET ratio falls below its threshold, as in drought events, the parameter sums decrease in response to the dryness. The second agroclimatic parameter is an indicator of the time period suitable for crop growth. The ‘sum of effective growing days’ parameter is similar to the previous parameter except that it is calculated as the number of days meeting each of the same four criteria of the first parameter. It also is affected by dryness when the ET ratio falls below the threshold, and the number of effective growing days decreases. The third agroclimatic parameter is used to indicate a water deficit during the growing season. The ‘number of dry days’ parameter is calculated as the number of days within a given period when the actual ET to reference ET ratio falls below 0.4. This particular parameter increases during drought events.

The results for this research were obtained from the three GCMs using an SRES-A2 scenario (IPCC, 2000). In general, although there was some variability between models, most of the results related to dryness or drought were fairly consistent spatially for each of the chosen GCMs. The results for one model, the Hadley-CM model, are displayed in Table 5.2 (for 2030) and Table 5.3 (for 2050). In Table 5.2, the effective global radiation and the number of effective growing days in 2030 decrease in the southern regions of Europe, with a slight increase or no change in the central and northern regions of the continent. For example, in the Pannonian zone, which is a major agricultural production region stretching from eastern Austria to the Black Sea (with an additional small region in southern Germany), the effective radiation and the number of effective growing days decrease by 11 per cent and 13 days by 2030, respectively. The number of dry days during the April–May–June period also shows the same pattern, with increases in southern Europe and either decreases or no change across central and northern Europe. The largest increase in dry days, by a little less than 10 per cent during this period by 2030, is

Table 5.2 Changes in the median values for selected agroclimatic indicators relative to the 1971–2000 reference period for 2030 based on the Hadley-CM model

EZ acronym	Effective global radiation change (%)	Effective growing days change (days)	Proportion of dry days in AMJ change (%)	Proportion of dry days in JJA change (%)
ALN	6	16	0	–2
BOR	4	11	0	1
NEM	5	9	1	4
ATN	0	3	–1	11
ALS	1	2	–2	9
CON	–3	–2	–1	11
ATC	–3	–4	–3	14
PAN	–11	–13	2	16
LUS	–9	–21	5	23
MDM	–7	–7	7	13
MDN	–7	–5	6	7
MDS	–14	–10	8	1

Note: For an explanation of the acronyms, see Table 5.1.

found in the Mediterranean zones. During the June–July–August period, the proportion of dry days increases across almost the entire continent by 2030 except for the Alpine North environmental zone. The increases by 2030 range from 14 per cent and 16 per cent in the Atlantic Central and Pannonian environmental zones (the two most intensive in terms of agriculture) to 23 per cent in the Lusitanian zone. In the Mediterranean zones, the number of dry days in the present climate classified as ‘dry’ is already high, so the percentage increase by 2030 is small. The patterns of the results for 2050 (Table 5.3) are very similar to the patterns for 2030, but the magnitudes of these changes are more pronounced. For example, the proportions of dry days in the June–August period increase 24 per cent, 25 per cent and 39 per cent in the Atlantic Central, Pannonian and Lusitanian zones by 2050, respectively.

These results indicate a gradient across Europe during the early months of the growing seasons in the future, with southern Europe having more potential for drought events. As the growing season progresses, however, the results indicate that almost all of Europe will have a greater potential for drought events during the mid-summer months.

These results and the other results collected by the research team confirm that there will be a northward expansion of the thermal suitability of crop production in Europe in the future. The drier summers in central and southern Europe will stress rainfed crop production in these regions, and the researchers suggest that irrigation will probably become more necessary. The combination of hotter and drier summers will certainly affect some of the highly productive agricultural regions across Europe, particularly in western France and parts of southeastern Europe (Hungary, Bulgaria, Romania and Serbia). The impacts will reduce crop yields and increase yield variability. The Mediterranean zones will also experience increased dryness in spring months, causing additional stress on rainfed crop production in these regions.

Table 5.3 *Changes in the median values for selected agroclimatic indicators relative to the 1971–2000 reference period for 2050 based on the Hadley-CM model*

EZ acronym	Effective global radiation change (%)	Effective growing days change (days)	Proportion of dry days in AMJ change (%)	Proportion of dry days in JJA change (%)
ALN	8	29	1	–2
BOR	8	16	–1	2
NEM	8	12	1	11
ATN	–1	5	–4	21
ALS	–1	0	–2	18
CON	–6	–6	–2	20
ATC	–6	–9	–4	24
PAN	–19	–19	5	25
LUS	–17	–39	14	39
MDM	–14	–15	10	21
MDN	–11	–11	13	11
MDS	–23	–20	13	1

Note: For an explanation of the acronyms, see Table 5.1.

Trnka and his colleagues have now begun efforts to connect these results with decision makers to incorporate their findings into planning activities and with other initiatives taking place on regional and global scales. The projected increase in the variability of climatic suitability for crop production in many of the prime agriculturally productive regions is particularly challenging for crop management and for agricultural policy, which aims to ensure stable food production and profitable conditions for producers. Strategies that help producers adjust to climatic variability and the projected changes should be investigated and implemented. Although this case study was conducted for Europe, similar results and conclusions are likely for other agricultural regions around the world.

CONCLUSION

This chapter looked at the important connection that exists between drought, agriculture and climate, and what that connection might look like in the future given current projections of climate variability and change, and their effects on the frequency, severity and duration of future drought episodes. The agricultural sector has always been vulnerable to a variety of natural and social factors, and this vulnerability is dynamic and constantly changing. Unfortunately, understanding agriculture's current vulnerability to climatic variability and its ability to cope with potential climate change impacts remains limited (Rosenberg, 2010; Field et al., 2007; Tol, 2002). Because drought and climate change share similar characteristics in terms of their long-term, slowly evolving or creeping nature, many lessons can be learned and applied from current efforts to implement drought risk management strategies today that can help prepare the agricultural sector

for a future that includes climate change. This will be important for a global society that is already facing critical food and water security issues. Learning to manage climatic variability today will help all countries deal more effectively with changes in climate in the future. Drought risk management must be a significant part of any climate change adaptation plan.

ACKNOWLEDGMENTS

The authors would like to thank both Deborah Wood with the NDMC and the anonymous reviewer for their thoughtful and helpful suggestions to improve the chapter. We would also like to acknowledge Mr Andrew Milevoj from California University of Pennsylvania for his assistance in identifying relevant materials for the chapter within the various IPCC reports. Dr Trnka's contribution was supported by COST 734 (CLIVAGRI), research plan No. MSM6215648905 and CzechGlobe (Centre for Global Climate Change Impacts Studies), Reg. No. CZ.1.05/1.1.00/02.0073.

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PART II

ECONOMIC STUDIES OF CLIMATE IMPACTS ON AGRICULTURE

6 Farm-level impacts of climate change: alternative approaches for modeling uncertainty

Dannele E. Peck and Richard M. Adams

INTRODUCTION

For more than two decades agricultural policy makers and stakeholders have expressed concern about the potential implications of global climate change for food security, resource management and the well-being of rural economies. In response, economists have applied several alternative methods at a variety of spatial and temporal scales to provide estimates of and insights into these potential impacts. Research has focused largely on estimating national and global impacts using highly aggregated data (e.g. Adams et al., 1990; Adams et al., 1999; Cline, 2007; Mendelsohn et al., 1994; Parry et al., 2004). Farm-level analyses, especially those employing mathematical programming techniques, have played a smaller role in climate change research. This is attributable, in part, to a lack of farm-level data for model parameterization, and the difficulty of downscaling climate change predictions to the local level. Heterogeneity of farms and operators also makes it difficult to scale farm-level results up to estimate aggregate impacts of climate change and associated policies.

Despite these challenges, farm-level mathematical programming models are useful because they can explicitly capture the decision-making environment in which climate change impacts and adaptations occur. This enables researchers to systematically alter components of the decision environment (e.g. management objectives and activities, resource constraints and information) to explore the effects of climate change on producer decisions; identify economically optimal adaptations; estimate climate change impacts, and test the value of information. Most large-scale (e.g. sector-level) models, in contrast, only implicitly capture the farm-level decision environment by identifying statistical relationships in data that emerged from that environment.

Because data used in these models are often aggregated to the regional level, many relevant details of the farm-level decision environment (e.g. crop rotations, as in El-Nazer and McCarl, 1986) are obscured, which limits the number of variables researchers can include to understand climate impacts and adaptations. Econometric approaches based on time-series or cross-sectional data, while useful for understanding heterogeneous impacts across time or space, are unable to assess the consequences of climate changes or management activities that fall outside the data's existing ranges.

One element of the farm-level decision environment, uncertainty, is particularly relevant to climate change research and not readily captured in either econometric approaches or large-scale models. Given the uncertainty surrounding climate change's future magnitude and physical consequences, it is important to consider how assumptions about uncertainty might affect economic impacts and optimal adaptation.

Farm-level mathematical programming provides a useful framework in which to capture uncertainty because it can explicitly represent it in a number of ways.

This chapter provides a description of alternative approaches for incorporating uncertainty in farm-level mathematical programming models, followed by a case study demonstrating each approach, a comparison of their respective impact estimates and a discussion of the limitations and opportunities for farm-level mathematical programming in future climate change research. Contributions of existing farm-level analyses to climate change research are highlighted throughout the chapter.

ALTERNATIVE APPROACHES TO UNCERTAINTY IN FARM-LEVEL PROGRAMMING MODELS

Introduction to Mathematical Programming

Mathematical programming (MP) represents a suite of optimization models, including both linear and non-linear programming, that have been used over the last 50 years to assess resource allocation and related economic decisions (see, e.g. Baumol, 1961), including farm management analyses (Hazell and Norton, 1986). MP models can be easily constructed and manipulated to simulate a variety of management scenarios. Equations (6.1)–(6.3) present a basic MP model with linear equations (known as linear programming, or LP).

$$\underset{x}{\text{Min}} z(x) = c^T x \quad (6.1)$$

subject to

$$Ax \leq b \quad (6.2)$$

$$x \geq 0 \quad (6.3)$$

where z is the objective value, x is a vector of decision (activity) variables, and c , A and b are vectors and matrices of known constants. In a farm management problem the elements of vector c often represent the per-unit cost of activities in vector x . Matrix A contains technical coefficients that express, for example, resource use per unit of x . Vector b would then represent the quantity of resources available for use.

Assumptions underlying this simple, deterministic specification of the LP model limit the analyst's ability to realistically represent decision-making processes. The assumption that all coefficients and relationships are known and constant, for example, is questionable in the context of climate change. Climate change is expected to increase the variability of weather and perhaps the inherent uncertainty underlying many farm systems as well (Meehl et al., 2007; Gutowski et al., 2008). Several MP approaches are capable of incorporating uncertainty; three such approaches, ranging from highly simplistic to more sophisticated, are described next. Each approach is applied to the same case-study farm system, in which climate change causes increased water supply variability. Results from the three approaches are compared to determine whether the

means by which uncertainty is modeled has important implications for climate change impact estimates.

Expected-value Approach

Early climate change studies emphasized shifts in mean surface air temperature and precipitation (annual or seasonal), because little was known at the time about potential changes in climatic variability (Folland et al., 1990). Predicted changes in mean values are most easily represented in farm-level MP models using the expected-value (EV) approach (not to be confused with mean-variance portfolio analysis, commonly denoted E-V analysis). The EV approach makes two simplifying assumptions: (1) each climatic variable of interest takes on one value, its mean (expected value), and (2) these climatic means are known at the time management decisions are made. Climatic variables' expected values are typically assumed to influence optimal farm management activities through crop yields (estimated using either a relatively simple production function or a more complex crop simulation model). The EV model is then solved twice: first assuming current climatic means, and then assuming predicted climatic means. Comparison of the two scenarios' objective function values generates an estimate of climate change impacts.

The EV approach ignores not only the inherent randomness of climatic variables, but also the fact that many farm-level decisions are made before climatic variables' values are revealed. Producers in the case-study region of eastern Oregon, for example, make some field preparation, planting and irrigation system decisions before their water supply for the upcoming growing season is known. The EV approach would assume in this case that water supply takes on only one value, its mean, and this value is known before management decisions are made. This relatively simple and deterministic approach to dealing with uncertainty is used only occasionally in climate change impact analyses, often couched within a more complex model of regional or national impacts (Erasmus et al., 2000).

More sophisticated versions of this deterministic approach account not only for climatic variables' means, but their variance as well (Finger and Schmid, 2007). These models still assume that each crop's mean and variance yield are known at the time farm management decisions are made. The goal, however, is to maximize expected utility, where the objective function reflects risk aversion. The model is solved once assuming current climate and crop yield means and variances, and again assuming means and variances associated with climate change to estimate impacts.

Passive Programming

Passive programming (PP) is a more general version of the EV approach. It assumes that decisions are made with perfect information about climatic variables. These variables, however, are assumed to be random with a discrete distribution of possible values. Because the random variables' values are realized before decisions are made, the problem is simply to characterize a distribution of possible outcomes (Cocks, 1968) by solving a deterministic programming problem for each realization of the random variable. The general notation for a PP problem is as follows:

$$\text{Min}_x z(x, s) = c_s^T x \quad (6.4)$$

subject to

$$A_s x \leq b_s \quad \forall s \quad (6.5)$$

$$x \geq 0 \quad (6.6)$$

The subscript s identifies coefficients whose values vary depending upon the state of nature being considered. Suppose, for example, that a producer's water supply (an element of vector b) differs between two states of nature (e.g. two climate change scenarios). The appropriate value of the resource coefficient is b_1 when climate change scenario 1 occurs, and b_2 when scenario 2 occurs. Similarly, coefficients in matrix A or vector c may vary with the climate change scenario. In the PP approach, equations (6.4) through (6.6) are solved for each state of nature. Distributions of optimal activity levels and objective values then arise from the collection of s solutions (Birge and Louveaux, 1997, p. 138). The expected value of the objective function, known as the wait-and-see solution, can also be calculated as follows (Cocks, 1968): $WS = E_s z(x^*(s), s)$. This provides an easy means to compare outcomes from scenarios that assume different distributions for climatic variables.

PP is essentially the analysis of an LP model's sensitivity to different values of the random variable (Higle and Wallace, 2003). The approach's relative simplicity is its advantage. PP requires the modeler to solve one programming problem for each possible value of the random variable. Once the initial model is developed, the PP problem only involves repeatedly changing parameter values in the program and resolving it.

Several economic studies use PP to explore climate change impacts (Gibbons and Ramsden, 2008; Mestre-Sanchis and Feijoo-Bello, 2009). They first solve a baseline version of the model for each value in the climate variable's initial distribution. This generates a baseline distribution of profit, or other outcomes of interest, from which expected value is calculated. This procedure is repeated assuming a new distribution for the random variable, which represents climate change. Outcomes of the baseline and climate change scenarios are then compared to estimate climate change impacts.

Passive programming's 'perfect information' solution can also be compared to 'imperfect information' solutions (such as those discussed in the next section) to determine the expected value of perfect information (Birge and Louveaux, 1997, p. 137). This comparison provides an upper bound on the value of improved weather forecasts and climate change predictions.

Stochastic Programming

PP imposes the unrealistic assumption that producers have full information when making decisions. In reality producers often face uncertainty about which realization of random climatic variables will be revealed in a given year. They might also face uncertainty about how climate change will affect the distribution of random climatic variables. These sources of uncertainty are particularly challenging for producers who make management decisions before uncertainty is resolved. A stochastic model, rather

than a deterministic one, is needed to explicitly capture the affect of uncertainty on these management decisions.

Stochastic programming, also known as discrete stochastic programming or discrete sequential stochastic programming (DSSP), was introduced by Cocks (1968) as a method for solving programming problems that include random variables as coefficients in constraints and the objective function. This approach accounts for the timing of decisions relative to information discovery. First-stage decisions are made prior to random variables' values being revealed. After decisions are made, some or all of the random variables' values are revealed. This resolution of uncertainty prompts second-stage (or recourse) decisions, which enable the decision maker to improve upon sub-optimal outcomes resulting from first-stage decisions made under imperfect information.

The general goal of DSSP is to choose first-stage activities that maximize current net benefits plus the expected net benefits of second-stage activities. The DSSP solution indicates optimal first-stage activities, as well as optimal recourse activities for each possible realization of the random variables. This approach, at least in its discrete form, is reminiscent of decision tree analysis (Hardaker et al., 2004, p. 203). The example DSSP model provided in equations (6.7) through (6.11) (Birge and Louveaux, 1997, p. 156) assumes, for simplicity, a single discrete random variable and a two-stage decision problem with recourse. It includes first-stage decision variables (x_i , which are indexed by activity), and second-stage decision variables (y_{is} , which are indexed by activity and state of nature). A set of second-stage decision variables and constraints exists for every state of nature. For numerical examples of the model, see Higle and Wallace (2003) and Birge and Louveaux (1997, p. 8).

$$\text{Max}_{x,y} z = - \sum_i c_i x_i + \sum_i \sum_s (r_{is} y_{is}) p_s \quad (6.7)$$

subject to

$$\sum_i x_i \leq L \quad (6.8)$$

$$\sum_i a_i y_{is} = W_s \quad \forall s \quad (6.9)$$

$$y_{is} \leq b_i x_i \quad \forall s, i \quad (6.10)$$

$$x_i, y_i \geq 0 \quad (6.11)$$

where

- x_i = a first-stage decision variable for the i th activity (e.g. acres of land prepared in the fall for crop i)
- c_i = a coefficient associated with activity x_i (e.g. cost associated with devoting an acre of land to crop i), known at the time x_i is chosen
- s = state of nature of a random variable (e.g. if water supply is the random variable, then s = dry, medium, wet)
- y_{is} = a second-stage decision variable for the i th activity given the s th state of nature occurs (e.g. acres of crop i to plant given state s has been revealed)

- r_{is} = a coefficient associated with activity y_{is} (e.g. revenue per acre of crop i given the s th state of nature is revealed)
- p_s = the probability of the s th state of nature occurring
- L = resource availability in the first stage (e.g. total land available)
- a_i = coefficient associated with activity y_{is} (e.g. acre-inches of water required per acre of crop i given the s th state of nature is revealed)
- W_s = resource availability given the s th state of nature is revealed (e.g. total irrigation water available)
- b_i = a coefficient linking second stage activity levels to first-stage activity levels (e.g. acres of crop i planted in the second stage cannot exceed acres prepared for crop i in the first stage, in which case $b_i = 1$).

Equation (6.7) demonstrates DSSP's goal of optimizing over both the current (first-stage) costs and the expected value of the future (second-stage) revenues. The expectation is taken over the probability distribution of the random variable. Note that the set of first-stage activities is $[x_1, x_2]$, and the set of second-stage activities is $[y_{1\ dry}, y_{1\ med}, y_{1\ wet}, y_{2\ dry}, y_{2\ med}, y_{2\ wet}]$. The number of random variables as well as the alternative states of nature that apply to each random variable strongly influence the number of second-stage decision variables. The set of constraints represented by equation (6.10) establishes the dynamic nature of the decision problem by linking first- and second-stage activities.

Constraints that apply only to first-stage decision variables, such as equation (6.8), are not contingent on the state of nature. Constraints involving second-stage decision variables, such as equation (6.9), must hold in every state of nature. The number of constraints therefore increases dramatically with the number of random variables and states of nature. This limits DSSP, in practice, to problems that involve few random variables and random variables with few realizations; otherwise, the 'curse of dimensionality' arises (Hardaker et al., 2004, p. 203).

Rae (1971) presents one of the first applications of DSSP to agriculture. Several economic studies have since used DSSP to explore optimal adaptations to climate change and estimate economic impacts (Adams and Peck, 2009; Connor et al., 2009; John et al., 2005; Kaiser et al., 1993). Most of these studies assume weather uncertainty (i.e. uncertainty about the value various weather variables will take on in any given year), but climate change certainty (i.e. certainty about which climate change scenario will occur in the future). They therefore solve the DSSP model separately for each climate change scenario rather than solving it once given probabilistic information about alternative climate change scenarios.

Models that explicitly capture the effects of weather uncertainty on farm-level decisions generate a more realistic baseline from which to explore climate change scenarios. Suppose for example that a producer faces uncertainty about the upcoming growing season's water supply; specifically, the producer knows only the probability of alternative scenarios. This uncertainty influences their crop mix and irrigation technology decisions for that year. Imagine, in contrast, how the decision might differ if the producer knew in advance that a drought would occur in the upcoming growing season. They would tailor management plans to include crops and irrigation technologies (or perhaps deficit irrigation levels) that perform best during drought. Under uncertainty, however, they

would design a plan that performs well, in expectation, across all states of nature. Any assessment of farm-level climate change impacts based on a model that abstracts from uncertainty, when producers actually face it, will predict farm management activities that are more tailored than is possible under uncertainty, and hence overestimate profit and underestimate climate change impacts.

Although DSSP is typically used to model weather uncertainty alone (i.e. climate change scenarios are often assumed known), it can be structured to represent both weather and climate change uncertainty, and perhaps should. A producer's crop and irrigation choices, after all, would likely differ if they knew exactly how climate would change, versus if they knew only the probabilities of alternative climate change scenarios. Although the economics literature on climate change notes the need to capture both weather and climate uncertainty within a stochastic framework (Connor et al., 2009; Schimmelpfennig, 1996), we are unable to identify any empirical studies that do so. The case study developed next represents a preliminary attempt to determine whether alternative assumptions about weather and climate uncertainty in a farm-level programming model significantly affect climate change impact estimates.

As noted earlier, one limitation of DSSP is that it becomes more difficult to solve as the number of random variables, realizations or stages increase. DSSP models are therefore often less complex than producers' actual decision-making environments. Nonetheless, solutions obtained from even relatively simple DSSP models are expected to generate more profit than solutions obtained from EV models (Rae, 1971). Unfortunately, the benefit of using DSSP rather than a simpler approach cannot be known *a priori* (Birge and Louveaux, 1997, p. 144). The following case study explores implications of using more sophisticated specifications of uncertainty in farm-level models of behavior and outcomes.

FARM-LEVEL MODELS WITH ALTERNATIVE UNCERTAINTY SPECIFICATIONS

Case-study Farm System

Four versions of a farm-level LP model are developed to represent alternative assumptions about uncertainty. All versions are based on a hypothetical irrigated row-crop farm in the Vale Oregon Irrigation District, a semi-arid region of the US Pacific Northwest (see Peck, 2006 for details). The area's primary source of irrigation water is snowmelt stored in small reservoirs with limited interannual carryover capacity. Drought is a major source of risk in the area, as in much of the semi-arid western USA, so water supply is the primary climatic variable of interest. Water scarcity is managed primarily through the following decision variables: crop acreage, crop mix, irrigation technology and deficit irrigation (and hence crop yields). These are the only forms of climate change adaptation assumed in the analysis.

A wide variety of crops can be grown in the study area, including onions, sugar beets, winter wheat, corn, alfalfa and potatoes. Crop rotations are therefore diverse and flexible. The suite of eligible crops for a particular field depends on the field's

physical characteristics (which are assumed, for simplicity, to be identical to other fields' characteristics), and a set of agronomic 'rules' that producers in the region typically follow. These agronomic rules, as defined in the analysis, prevent individual crops from being planted in the same field more often than producers recommend. This reduces pest and disease outbreaks to levels producers typically consider acceptable.

Constrained by a set of eligible crops for each field in a given year, the producer chooses one crop and irrigation system per field, taking into consideration relative profitability and water supply. The choice of an irrigation system is simplified in the analysis by assuming that a new system can be adopted each year, and that its annualized costs are incurred only in years it is used. This implies that a field's irrigation system can either be moved to another location (if needed elsewhere) or sold for the balance owed. The extent to which water supply is known in advance varies by modeling approach. The producer, who is assumed risk-neutral, faces a multi-year, dynamic and (in some cases) stochastic decision problem, with the objective to maximize discounted returns (or discounted expected returns in stochastic versions of the model) over a three-year planning horizon.

Water supplies are finite in each year of each version of the model. In deterministic versions of the model (that is, EV and PP approaches), water supplies in all three years of the planning horizon are known at the time decisions are made. In the stochastic version of the model (that is, the DSSP approach), the upcoming growing season's water supply is uncertain when field preparation and planting decisions are made in the fall (as are supplies in future years). After the water allotment is revealed in mid-spring the producer responds by planting or abandoning fields prepared in the fall. They might also deficit-irrigate some of the fields selected for planting if water is sufficiently scarce. The planted crop's value and sensitivity to alternative levels of water deficit, as well as the opportunity cost of water, drive this decision.

All versions of the model investigate three climate scenarios: a scenario based on current conditions (baseline); a scenario in which climate change causes average precipitation to increase (increased EV); and a scenario in which climate change causes average precipitation to decline (decreased EV). Each climate scenario contains three states of nature (dry, medium, wet), which represent alternative irrigation water supplies (measured in acre-inches per acre of land) that could be available during the growing season. Table 6.1 presents the magnitude and probability assigned to each state of nature in each climate scenario.

Magnitudes of water supplies for states of nature in the baseline scenario are based on historical data and information that producers in the region provided (e.g. 40 acre-inches of water per acre is considered sufficient to implement most crop plans and 20 acre-inches of water per acre is representative of an agronomic shortage). Probabilities in the baseline scenario are hypothetical; they were chosen to simplify construction of the climate change scenarios. Magnitudes and probabilities for the two climate change scenarios are also hypothetical. They were chosen to represent approximately a 10 per cent increase or decrease in the expected value of the water supply (relative to the baseline scenario's expected value), as well as more frequent and extreme dry and wet years (as predicted for many regions by Gutowski et al., 2008 and Meehl et al., 2007).

Table 6.1 Quantities of irrigation water available under three different climate scenarios

Climate scenarios under certainty	Quantity of available irrigation water (in acre-inches per acre of land), and probability (%), for each state of nature			
	Dry	Medium	Wet	Expected value
Baseline	24 (25)	32 (50)	40 (25)	32
Increased EV	20 (30)	32 (30)	51 (40)	36
Decreased EV	13 (40)	32 (30)	44 (30)	28

Note: Each scenario comprises three states of nature (dry, medium, wet) whose probabilities sum to one. The two climate change scenarios ('Increased EV' and 'Decreased EV') represent a 10 per cent increase or decrease in the baseline water supply's expected value, and an increase in the frequency and intensity of extreme events.

Expected-Value Approach

The EV version of the model maximizes discounted returns to land and management by choosing a crop, irrigation technology and deficit irrigation level for each of the farm's ten fields (35 acres each) in each year of a three-year planning horizon. Irrigation water supplies in all three years are known before first-year decisions must be made. Water supplies are assumed equal to the relevant climate scenario's expected value: 32, 36 and 28 acre-inches per acre for the baseline, increased EV and decreased EV scenarios, respectively (Table 6.1). The EV model is solved once for each climate scenario; discounted profit for each scenario is reported in Table 6.2. Optimal crop and irrigation activities are identified in the solution, but not reported here.

Under the EV approach, the 'increased EV' and 'decreased EV' scenarios cause only small changes (+1 per cent and -3 per cent, respectively) in discounted profit relative to the baseline scenario (Table 6.2). This is because the change in water supply triggered by climate change is known before all crop and irrigation decisions are made. It is also because a 4-inch change in water supply is insufficient to cause an agronomic water surplus (or deficit) situation.

Producers in the study area do not, in reality, receive the expected value of irrigation water every year; water supply varies from year to year. The EV approach therefore imposes an overly optimistic assumption about water supply variability. The question of interest is whether climate change impact estimates are sensitive to alternative assumptions about variability and uncertainty. Next we explore the passive programming approach and compare its climate change impact estimates to those from the simple but unrealistic expected-value approach.

Passive Programming

Passive programming (PP) imposes more realistic assumptions about the farm's water supply than the EV approach. Specifically it allows water supply to vary from year to year, although those quantities are still assumed to be known at the start of the planning horizon. Because each climate scenario includes three possible states of nature (dry,

Table 6.2 Discounted profit under three different climate scenarios using the expected-value approach

Climate scenario	Value at optimal solution
Baseline (32 acre-inches per acre of land each year)	
Discounted profit	\$498 732
Increased EV (36 each year)	
Discounted profit	\$504 017
Absolute change from baseline	\$5286
Per cent change from baseline	1
Decreased EV (28 each year)	
Discounted profit	\$484 764
Absolute change from baseline	–\$13 968
Per cent change from baseline	–3

Table 6.3 Discounted profit under various climate scenarios using passive programming

Climate scenario	Expected Profit	Minimum Profit	Maximum Profit	Standard Deviation
Baseline	\$495 723	\$461 305	\$523 311	\$15 033
Increased EV	\$504 017	\$446 203	\$544 332	\$25 250
Absolute change from baseline	\$8294	–\$15 102	\$21 021	\$10 217
Per cent change from baseline	2	–3	4	68
Decreased EV	\$470 585	\$394 180	\$535 216	\$34 904
Absolute change from baseline	– \$25 138	–\$67 125	\$11 905	\$19 872
Per cent change from baseline	–5	–15	2	132

Note: Three states of nature are possible in each year of the model. A climate scenario therefore comprises multiple water supply situations, ranging from three dry years to three wet years and all combinations in between. Solving the model for every water supply situation generates a profit distribution. Summary statistics for each climate scenario's profit distribution are presented.

medium wet), and the planning horizon spans three years, 27 alternative water supply situations are possible. The PP approach solves a deterministic version of the model for each of the water supply situations possible in a given climate scenario. This process is repeated for each climate scenario. The solutions to a particular climate scenario include 27 profit outcomes and management plans. Summary statistics for each climate scenario's profit outcomes are reported in Table 6.3.

Although probabilities are not directly used in the PP approach, we can combine them with profit outcomes to estimate expected profit (a process that generates the wait-and-see solution) for each climate scenario. Comparison of expected profit across scenarios reveals that climate change does not have a major effect when the water supply is perfectly anticipated (Table 6.3). This is the same conclusion reached using the EV approach, although PP suggests slightly larger impacts to expected profit.

PP reveals an additional insight regarding the impacts of climate change on profit variability. Recall first that climate change is assumed to affect not only average water supply, but also the frequency and intensity of extreme events. The EV approach only implicitly incorporates extreme events through their impact on the water supply's expected value. This tempers the effect of extreme events on farm management. PP, in contrast, incorporates extreme events directly as states of nature in an expanded set of water supply situations. As a result, extreme events cause farm management plans and profit to vary across water supply situations.

Changes in the intensity of extreme events cause alternative states of nature to diverge from one another. This causes farm management activities for alternative water supply situations to be less similar, and hence profit variability to increase. Increased profit variability is highly relevant to risk-averse producers and to administrators of government policies such as crop insurance and disaster assistance. Unlike the EV approach, the PP approach is capable of identifying climate change's effect on profit variability. This indicates that variation in climatic variables, even under the assumption of certainty, has important implications for climate change impact estimates.

Stochastic Programming: Uncertain Weather but Certain Climate Change

The EV and PP approaches both assume that water supplies are known with certainty before management decisions have to be made. Most producers, however, have only probabilistic information about the upcoming growing season's water supply, and must make management decisions before the actual water supply is revealed. This is particularly true for rainfed farms or those that rely on small reservoirs with no interannual storage capacity. DSSP enables analysts to model water supply uncertainty more realistically by accounting for the timing of management decisions relative to the availability of information about water supply.

In this initial application of DSSP we assume the producer knows which of the three climate scenarios (baseline, increased EV or decreased EV) is occurring and therefore which water supply distribution to use in their decision-making problem. They do not know, however, which state of nature (dry, medium or wet) will be revealed in the upcoming growing season, or in future years. Before the upcoming growing season's water supply is revealed, they must prepare fields, choose irrigation technologies and sow any fall-planted crops (first-stage decisions). After the water supply is revealed they make all remaining decisions for the crop year, including whether to abandon or irrigate fall-planted fields, whether to fallow or plant fall-prepared fields and whether to deficit-irrigate any planted fields (second-stage decisions).

First-stage decisions impose constraints on second-stage decisions, and second-stage decisions impose constraints on decisions in future years. The producer therefore faces a decision problem that is both stochastic and dynamic (i.e. the model is forward looking). See the supplemental appendix to Peck and Adams (2010) for the theoretical model; note however that the six-year model in Peck and Adams (2010) is reduced here to three years to avoid the curse of dimensionality, which arises when states of nature for both weather and climate uncertainty are included. This version of the DSSP model is solved three times, once for each climate scenario. Results from each climate scenario (Table 6.4) are then compared to determine climate change impacts.

Table 6.4 Discounted profit under various climate scenarios using discrete sequential stochastic programming

Climate scenario	Expected Profit	Minimum Profit	Maximum Profit	Standard Deviation
Baseline	\$479 759	\$430 876	\$494 638	\$16 783
Increased EV	\$465 847	\$397 208	\$495 600	\$26 906
Absolute change from baseline	-\$13 912	-\$33 669	\$962	\$10 123
Per cent change from baseline	-3	-8	<1	60
Decreased EV	\$417 214	\$324 553	\$479 594	\$43 077
Absolute change from baseline	-\$62 545	-\$106 323	-\$15 043	\$26 294
Per cent change from baseline	-13	-25	-3	157

Note: Water supply uncertainty and climate change certainty are assumed. Three states of nature are possible in each year of the model, so each climate scenario comprises many water supply situations, ranging from three dry years to three wet years and all combinations in between. The model is solved once for each climate scenario. This generates a distribution of profit outcomes for each. Summary statistics for the distributions are presented.

When the producer faces weather uncertainty but climate certainty, several notable climate change impacts emerge. First, the climate scenario in which the water supply's expected value increases by 10 per cent and the frequency and intensity of extreme events increase (i.e. the increased EV scenario) causes a 3 per cent decrease in expected profit, as compared to the 1 to 2 per cent increase indicated by the deterministic approaches. Second, the climate scenario in which the water supply's expected value decreases by 10 per cent and the frequency and intensity of extreme events increase (i.e. the decreased EV scenario) causes a 13 per cent decrease in expected profit, as compared to the 3 to 5 per cent decrease indicated by the deterministic approaches. Third, both climate scenarios cause larger decreases in minimum profit than the deterministic approaches indicate. Finally, climate change, as represented in the DSSP model, does not increase maximum profit; it remains unchanged or declines (Table 6.4). Even though the DSSP model assumes that excess water helps rather than harms crop yields, the model is unable to take advantage of more extreme wet years due to weather uncertainty.

DSSP results indicate that if producers face water supply uncertainty in their day-to-day decision environment, and if climate change causes more frequent and intense extreme events, then their adaptation will be less effective than deterministic models suggest. Under water supply uncertainty, the model chooses management activities based on their relative performance under different states of nature (weighted by their respective probabilities). When alternative states of nature are similar, as in the baseline scenario (or in the EV approach as an extreme example), it is easier to identify a single management plan that performs well across different states. When states of nature are highly dissimilar, however, it is more difficult to identify a single plan that performs well across the different states. The model must either develop a plan that performs well in the event of extreme drought, but not in extreme wet (or vice versa), or a plan that performs well in years of moderate water, but not in extremely dry or wet years.

The result is a three-year crop plan that generates less expected profit, suffers greater losses during extreme drought events and generates smaller gains during abundant water years.

This finding makes intuitive sense and has been hypothesized by others in the literature (Mendelsohn, 2000). The case study demonstrates the finding clearly, however, by comparing deterministic and stochastic versions of the same model. More precisely, this study shows that the magnitude of farm-level impacts resulting from more frequent and intense extreme events is quite sensitive to assumptions about weather uncertainty. The choice between deterministic and stochastic modeling approaches should therefore be made carefully, with consideration for the presence or absence of weather uncertainty in farm systems.

The use of deterministic versus stochastic modeling approaches also has implications for optimal farm management activities. A thorough discussion of optimal crop and irrigation activities for each modeling approach and climate scenario is beyond the scope of this chapter. However, a comparison of a subset of the PP and DSSP models' solutions reveals interesting similarities and differences in climate change adaptation strategies under weather certainty (PP) versus uncertainty (DSSP). Comparison of the baseline versus decreased EV scenarios' solutions, for example, reveals that under a drier and more extreme climate, both modeling approaches recommend more fallowing, more efficient irrigation for certain crops and more even distribution of high-valued crops across years. Under certainty, these strategies are implemented only in years of drought. Under weather uncertainty, however, these strategies are implemented in all years. This minimizes losses during drought but generates opportunity costs (foregone profit) during years of abundant water.

The PP and DSSP models' climate change adaptation recommendations have several features in common but they also have some differences. Wheat and sugar beet's roles in drought management, for example, differ under certainty versus uncertainty. Under certainty, wheat is planted in years of drought, whereas sugar beet is planted in years of abundant water. Under uncertainty, it is not known in advance whether water will be scarce or abundant, so it is less clear whether wheat or sugar beet should be planted. Given the probability and severity of drought the DSSP model recommends preparing more fields for sugar beet than wheat.

Although wheat requires less water than sugar beet and is less sensitive to water stress, it is less profitable under full irrigation and requires larger fall investments. The first two features make wheat an attractive drought management tool. Under weather uncertainty, however, the last two features make it less attractive. The DSSP model favors sugar beet because it performs better than wheat in expectation. Specifically in the event of drought, sugar beet is cheaper to abandon than wheat (because fall investment costs are lower), and in the event of abundant water, sugar beet is more profitable than wheat. This result highlights the potential for deterministic modeling approaches to recommend management activities that are not necessarily optimal under uncertainty. Again, the choice between deterministic and stochastic modeling approaches should be made with consideration for the presence or absence of uncertainty in the farm system of interest.

Stochastic Programming with Both Weather and Climate Change Uncertainty

The previous application of DSSP assumes weather uncertainty, but certainty about which climate change scenario occurs. For many regions of the world, scientists do not yet know whether climate change will cause average water supplies to increase or decrease (although extreme events are likely to become more frequent and intense in either case) (Gutowski et al., 2008; Meehl et al., 2007). Producers in these regions therefore face both weather uncertainty and climate change uncertainty, which further complicates adaptation. In the following DSSP specification, we address both forms of uncertainty.

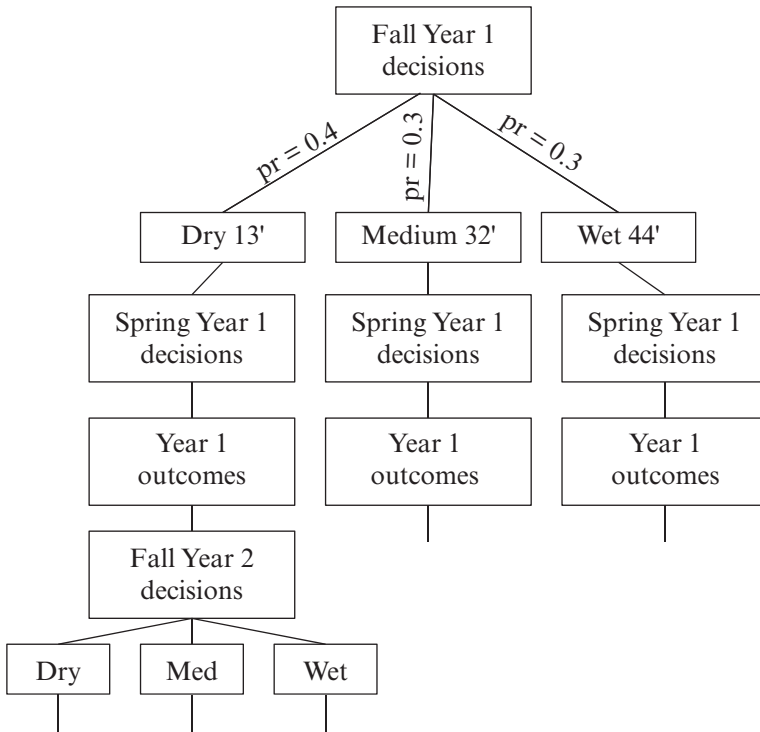
In this version of the DSSP model, the producer is assumed to know that climate change is going to occur, but does not know whether the ‘increased EV’ or ‘decreased EV’ scenario will prevail. With no information about which scenario is more likely, a 50 per cent probability is assigned to each. Given the model’s relatively short timeframe, we assume that the producer does not learn over the three-year horizon which climate change scenario is occurring. This assumption allows the probability of each climate scenario to remain unchanged through time.

Climate uncertainty, as modeled here, represents an additional branch on the DSSP decision tree, located above branches associated with water supply uncertainty (i.e. Figure 6.1 is transformed into Figure 6.2). As in the previous DSSP model, recourse decisions are made after the water supply in a particular year is revealed. Because the climate change scenario is never explicitly revealed to the producer, climate change uncertainty does not create additional decision nodes. As a result we can compact the decision tree by multiplying the probability of each water supply situation by the probability of its respective climate change scenario, and redefine the states of nature (i.e. transform Figure 6.2 into Figure 6.3).

The DSSP model accounts for both climate change scenarios simultaneously and is therefore solved just once (Table 6.5). It does not, however, include a baseline scenario. ‘Baseline’ results in Table 6.4 provide the appropriate benchmark for comparison because they are derived assuming weather uncertainty and no climate change. In contrast, results in Table 6.5 are derived assuming weather uncertainty and climate change uncertainty. Comparison of these results isolates the effects of uncertain climate change on producers who also face weather uncertainty.

The proposed comparison is not as straightforward as it may seem. When climate change is uncertain, impact estimates depend on whether expected profit is calculated using the full set or just a subset of profit outcomes (Table 6.5). The structure of the DSSP model used in this subsection (Figure 6.3) implies that the producer believes any combination of the two climate change scenarios’ states of nature are possible over the three-year planning horizon. In reality, only one climate change scenario will occur, either ‘increased EV’ or ‘decreased EV.’ Any water supply situation that involves states of nature from both is implausible and should be ignored.¹

Suppose we ignore reality for a moment and calculate expected profit using outcomes from all 125 water supply situations (see ‘Uncertain climate change (all)’ in Table 6.5). This represents expected profit when the producer plans for all 125 water supply situations, and all situations are actually possible, including combinations of climate change scenarios. Suppose we instead calculate expected profit using profits only from the 27 water supply situations possible in the ‘increased EV’ scenario (see ‘Uncertain climate



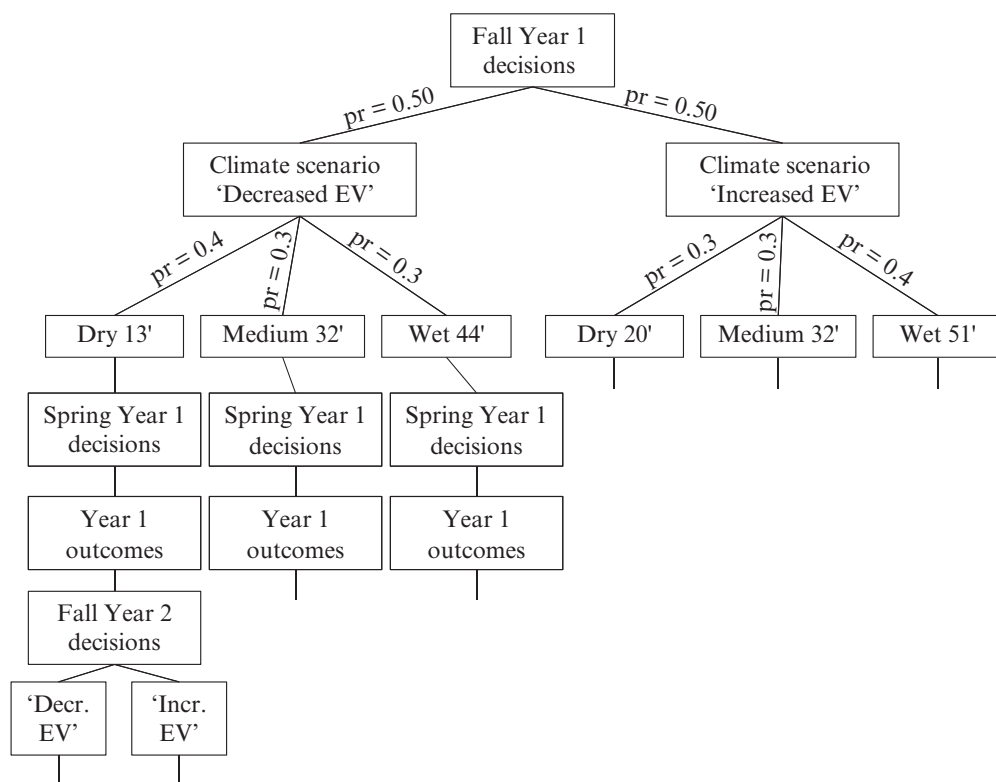
Note: In the DSSP model, some management decisions are made in the fall, before the water supply is revealed, while others are made in the spring, after the water supply is revealed.

Figure 6.1 Decision-tree representation of the discrete sequential stochastic programming model assuming water supply uncertainty, but climate change certainty

change (incr.)' in Table 6.5).² This represents expected profit when the producer plans for all 125 water supply situations, but the 'increased EV' scenario, unbeknownst to them, will occur. We could similarly use only profits associated with the 'decreased EV' scenario's 27 water supply situations (see 'Uncertain climate change (decr.)' in Table 6.5).

The weighted average of expected profits from 'Uncertain climate change (incr.)' and 'Uncertain climate change (decr.)' represents expected profit when the producer plans for all 125 water supply situations, but only 54 of the situations are actually plausible (i.e. states of nature will arise from one of the two possible climate change scenarios; see 'Uncertain climate change (plaus.)' in Table 6.5). Comparison of the weighted average expected profit when the 54 plausible situations are used with expected profit when all 125 water supply situations are used reveals no noticeable difference in impact estimates.³ Impact estimates from the latter are therefore used in all cross-model comparisons.

Impact estimates from the DSSP model that assumes both weather and climate uncertainty (Table 6.5) are in the same range as those from the DSSP model that assumes weather uncertainty but climate change certainty (Table 6.4). The 'increased EV' scenario for example causes a 3 per cent decline in expected profit when the producer knows

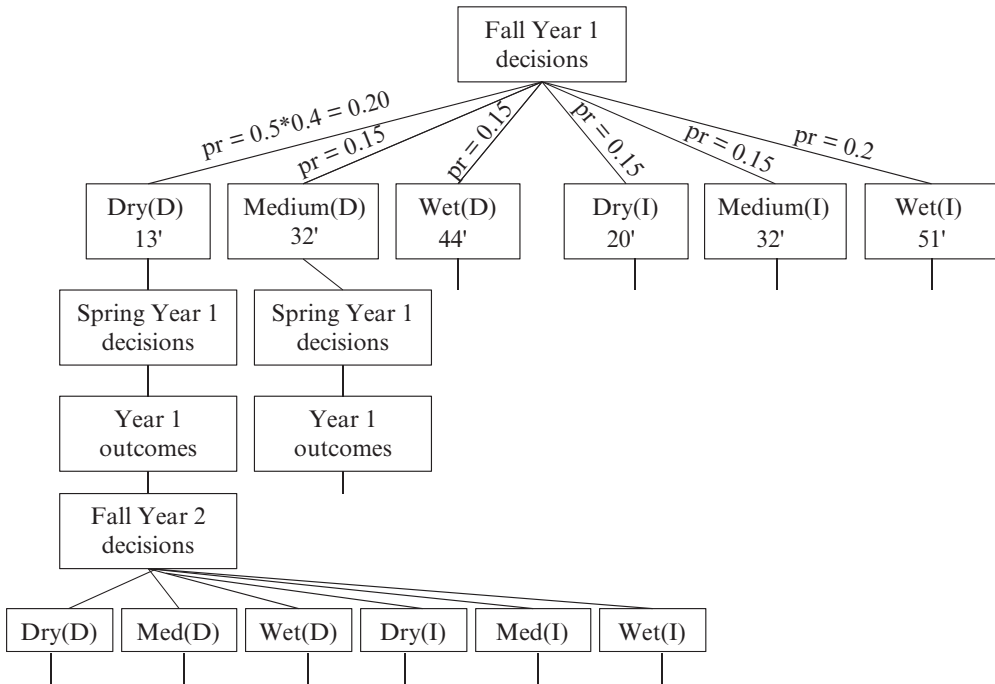


Note: In the DSSP model, some management decisions are made in the fall, before the water supply is revealed, while others are made in the spring, after the water supply is revealed.

Figure 6.2 Decision-tree representation of the discrete sequential stochastic programming model assuming water supply and climate change uncertainty, with the two sources of uncertainty shown separately

it will occur ('Increased EV' in Table 6.4), compared to a 5 per cent decline when the producer does not know which climate change scenario will occur. A similar comparison for the 'decreased EV' scenario indicates a 13 per cent decline when the producer knows it will occur ('Decreased EV' in Table 6.4) versus a 14 per cent decline when climate change is uncertain. Estimated changes in minimum, maximum and standard deviation of profit are also similar between the two models.

The decision environments represented in the two DSSP models are different in ways that *a priori* seem important. Specifically, the models make different assumptions about the timing of producer decisions relative to climate change information. Results indicate, however, that explicit modeling of climate uncertainty has little effect on expected profit when weather uncertainty is also modeled. These findings suggest that in the face of weather uncertainty, climate change uncertainty does not significantly alter farm-level outcomes. For producers who already face weather uncertainty, climate change uncertainty essentially adds more states of nature to their decision problem, or (in the case of a



Note: In the DSSP model, some management decisions are made in the fall, before the water supply is revealed, while others are made in the spring, after the water supply is revealed.

Figure 6.3 Decision-tree representation of the discrete sequential stochastic programming model assuming water supply uncertainty and climate change uncertainty, with the two sources of uncertainty collapsed into one joint probability

continuous water supply variable) shifts the water supply's probability distribution. This finding may be attributable to optimal adaptations performing equally well under either climate change scenario. Alternatively, the irrigated farm system modeled here might be less vulnerable to climate uncertainty than other systems. Further investigations are needed to test these hypotheses.

SUMMARY AND DISCUSSION OF CASE-STUDY FINDINGS

The case study presented above explores the importance of (1) using deterministic versus stochastic programming models in climate change impact studies, and (2) imposing alternative assumptions about weather and climate uncertainty in stochastic models of climate change impacts. It is clear for this particular case study that although the assumption of weather uncertainty has important implications for the magnitude of climate change impacts, the assumption of climate change uncertainty has relatively little effect.

Table 6.5 Discounted profit using discrete sequential stochastic programming

Climate Scenario	Expected Profit	Minimum Profit	Maximum Profit	Standard Deviation
Uncertain climate change (all) ^a	\$432 802	\$307 225	\$486 265	\$41 818
Absolute change from baseline	-\$46 956	-\$123 652	-\$8372	\$25 035
Per cent change from baseline	-10	-29	-2	149
Uncertain climate change (incr.) ^b	\$453 498	\$386 788	\$484 048	\$26 997
Absolute change from baseline	-\$26 261	-\$44 089	-\$10 590	\$10 214
Per cent change from baseline	-5	-10	-2	61
Uncertain climate change (decr.) ^c	\$411 592	\$307 225	\$484 596	\$49 663
Absolute change from baseline	-\$68 167	-\$123 652	-\$10 041	\$32 880
Per cent change from baseline	-14	-29	-2	196
Uncertain climate change (plaus.) ^d	\$432 545	\$307 225	\$484 596	\$41 750
Absolute change from baseline	-\$47 214	-\$123 652	-\$10 041	\$24 967
Per cent change from baseline	-10	-29	-2	149

Notes: Both water supply uncertainty and climate change uncertainty are assumed. Five states of nature are possible in each year of the model. States of nature, characterized by quantity of available water (in acre-inches per acre of land) and probability, are as follows: 13" (20 per cent), 20" (15 per cent), 32" (30 per cent), 44" (15 per cent), 51" (20 per cent). Results are compared with the 'Baseline' in Table 6.4, which assumes weather uncertainty, no climate change (and hence no climate change uncertainty), and the following characteristics for states of nature: 24" (25 per cent), 32" (50 per cent), 40" (25 per cent).

- Expected profit for this scenario is calculated over all 125 realizations of the water supply situation. It assumes all combinations of water supplies are possible, even those that combine states of nature from the two different climate change scenarios, e.g. 13" in year 1, 20" in year 2, 51" in year 3, or Dry(Decreased EV) in year 1, Dry(Increased EV) in year 2, Wet(Increased EV) in year 3.
- Expected profit for this scenario is calculated using only the 27 realizations of water supply situations possible when the 'Increased EV' climate change scenario occurs, unbeknownst to the producer. Profit outcomes are weighted using the 'Increased EV' scenario's original probabilities: 20" (30 per cent), 32" (30 per cent), 51" (40 per cent).
- Expected profit for this scenario is calculated only over the 27 realizations of water supply situations possible when the 'Decreased EV' climate change scenario occurs, unbeknownst to the producer. Profit outcomes are weighted using the 'Decreased EV' scenario's original probabilities: 13" (40 per cent), 32" (30 per cent), 44" (30 per cent).
- Expected profit for this scenario is calculated as the average of expected profit from the 'Uncertain climate change (incr.)' and 'Uncertain climate change (decr.)' scenarios. Minimum, maximum, and standard deviation are based on profits from water supply situations that do not include states of nature from both 'Increased EV' and 'Decreased EV'.

In the absence of weather uncertainty (i.e. in deterministic approaches such as EV and PP), the hypothetical producer perfectly anticipates future water supplies, including the effects of climate change on those supplies. The producer can therefore mitigate the negative effects of more extreme drought and take advantage of the positive effects of more extreme wet years without worrying about under- or over-adapting. As a result, climate change impacts are relatively small and even positive in some cases.

In the presence of weather uncertainty (i.e. in stochastic approaches, such as DSSP), the producer does not know which water supply situation will occur and therefore cannot tailor management plans to each water supply situation. They must instead develop a single plan that performs well, in expectation, over all possible situations.

As alternative water supply situations become more diverse because of climate change, it becomes more challenging to identify a single plan that performs well across the suite of possible situations, and hence expected profit declines. Weather uncertainty, it seems, can magnify climate change impacts even when the climate change scenario is known in advance. Deterministic programming approaches, when applied to farm systems that are subject to weather uncertainty, will tend to underestimate climate change impacts. Producers and policy makers could, as a result, receive overly optimistic predictions of climate change impacts and subsequently under-invest in adaptation.

The above results provide insights not only into the advantages and shortcomings of alternative farm-level programming approaches, but also into the value of improved weather and climate change forecasts. Results specifically reveal that improved climate change forecasts would only slightly reduce climate change impacts. Improved long-term weather forecasts, in contrast (e.g. water supply forecasts with six-month lead times), would reduce impacts significantly, at least in farm systems that require management decisions to be made before weather uncertainty is resolved.

The relative importance of weather uncertainty versus climate change uncertainty will depend on the suite of tactical (short-term) versus strategic (long-term) management tools available to the farm system. The model used here does not consider strategic management responses such as introducing new crops, purchasing new equipment, building new reservoirs or converting farmland to non-farm uses. For farm systems in which strategic management options are relevant, or weather conditions are less variable, improved climate change predictions will be more valuable than seasonal weather forecasts. For farm systems in which management options are largely tactical, the opposite will be true.

This case study focuses specifically on irrigated crop systems; however, weather and climate variability and uncertainty also affect livestock and rainfed crop production. It is well documented, for example, that ambient air temperature influences livestock feed intake, weight gain, reproduction and mortality (St Pierre et al., 2003). Rainfall affects forage availability and quality for feedlot and rangeland livestock (Torell et al., 2011). Uncertainty about the timing, duration, intensity and probability of weather events has important implications for livestock management and profitability (Ritten et al., 2010). Possible short-term adjustments might include provision of additional shade and water to mitigate heat stress, increased supplemental feeding during drought and changes in feed composition. Long-term adjustments might include selection of more heat-tolerant breeds and reduction of herd sizes to accommodate more variable forage supplies (Hurd et al., 2007; Rowlinson, 2008).

Weather variability and climate change also affect rainfed crop production. Temperature, growing-season length, and the quantity, timing and intensity of rainfall have important implications for crop yield, management and profitability (Adams et al., 2003; Rosenzweig et al., 2002). Increasing variability in these factors due to climate change will impose additional uncertainty on rainfed crop producers. Farm-level responses to temperature and rainfall variability in the short term might include adoption of new crop varieties, earlier planting dates and increased participation in crop insurance, disaster assistance and weather-forecasting services. Long-term adjustments might include planting new crop species, shifting from crop-only to mixed crop–livestock systems, investing in supplemental water supplies and adopting new tillage or drainage

practices (to accommodate more extreme precipitation events) (Mendelsohn and Seo, 2007).

The effects of weather variability and climate change on rainfed agriculture and livestock production have been investigated in numerous studies, many of which use farm-level mathematical programming models. A comparative analysis to determine the relative importance of weather versus climate change uncertainty in these systems would be a useful extension of the case study presented here for irrigated agriculture. The cost of improving weather versus climate change forecasts would also be relevant to the discussion.

CHALLENGES AND OPPORTUNITIES FOR FARM-LEVEL PROGRAMMING IN CLIMATE CHANGE RESEARCH

Farm decision environments and producer behavior are, in reality, far more complex than most climate change models (including ours) assume. Although the complexity of programming models is improving (e.g. John et al., 2005; Kaiser et al., 1993; Dickinson, 2007), their most salient feature, optimization, limits the amount of realism they can accommodate. Complex decision processes, for example, are often distilled into relatively simple objective functions that ignore relevant drivers of behavior such as risk preferences, perceptions of vulnerability, attitudes to coping and loss, inertia in decisions, perceived self-efficacy, constraints to learning and other non-expected utility processes (Grothmann and Patt, 2005; Patt et al., 2010; Tol et al., 1998). Furthermore, climate change is rarely evaluated in the context of other risks (Bradshaw, 2007). A producer with limited risk management resources may choose to allocate them to other sources of risk, such as price variability or pest management rather than climate change adaptation (Grothmann and Patt, 2005).

Few analyses include government programs and policies such as crop insurance, direct payments and disaster assistance, despite their potential to influence farm-level adaptation to climate change (Smit and Skinner, 2002). Lastly, studies rarely model the full range of adaptation tools (whether new or existing) from which producers can choose, including field-level (e.g. deficit irrigation), farm-scale (e.g. enterprise diversification, crop insurance, carbon credits), and off-farm (non-farm income) activities (Howden, 2003). Model specification simply becomes too cumbersome and optimization infeasible when analysts attempt to tackle several features of the farm system at once.

Heterogeneity in farm characteristics and producer behavior poses another challenge to farm-level models. The relevance of this challenge for any particular climate change study depends, of course, on the study's purpose. If a study intends to evaluate alternative adaptation tools, the programming model's objective function (which reflects the hypothetical producer's goals, risk preferences, discount rate etc.) and constraints (which reflect the farm's resources, productivity and limits to management skill) determine the set of optimal adaptation tools. Adaptation recommendations must therefore be prefaced with a large set of underlying assumptions, making them difficult to generalize to other situations.

Studies that use stochastic MP approaches are particularly vulnerable to oversimplification. Dimensionality problems often require tradeoffs between the complexity of the

objective function and constraints, the number of states of nature and the number of decision periods. Deterministic approaches can accommodate more complex functions and decision periods but they abstract from uncertainties in the decision environment whose relevance we have demonstrated. Simulation approaches can accommodate more details about the physical environment and many time-steps; however, they lack objective functions and are therefore unable to identify 'optimal' adaptation activities. Again, tradeoffs must be made based on individual studies' specific goals.

One final challenge for all farm-level programming studies, whether stochastic or deterministic, is a more realistic treatment of the gradual and subtle nature of climate change (Kaiser et al., 1993). Most programming models assume that climate change happens instantaneously, and that producers automatically detect its occurrence and implement optimal adaptations. In reality, climate change scenarios may unfold over a producer's lifespan. The speed at which climate change occurs relative to producers' discount rates will affect the timing and extent of adaptations. As more frequent extreme events make it increasingly clear to producers that the current climate regime is changing, they are likely to make gradual adaptations (Negri et al., 2005; Patt et al., 2010). Most assessments, regardless of the approach, have ignored questions about the optimal transition path in response to gradual climate change.

Although individual models have collectively addressed numerous aspects of the complex farm decision environment, few MP models have addressed multiple aspects simultaneously in an integrated framework. We have demonstrated through a simple case study that weather uncertainty can have important implications for climate change impacts. More complex models are needed, however, to test whether this conclusion holds in the presence of alternative management objectives, other forms of risk, a longer timeframe with a larger suite of adaptation tools and a more realistic representation of gradual climate change and learning. The challenges that remain for farm-level programming models of climate change should be viewed as an abundant source of future research opportunities.

NOTES

1. This complication arises because the model includes multiple years with recourse decisions made each year after the water supply is revealed. It would not arise in a single-year model and could be avoided in a simpler multi-year model. For example, if water supplies for all years were simultaneously realized followed by a single round of recourse decisions, the random variable could be the 'three-year water supply', and states of nature could be defined to include only plausible situations, such as Dry(I), Dry(I), Wet(I), or Dry(D), Dry(D), Wet(D), but not Dry(I), Dry(I), Wet(D). When states of nature are revealed sequentially across years (as they are in our DSSP model) rather than simultaneously (as proposed in this note), conditional probabilities would be needed to avoid implausible water supply situations. Conditional probabilities would imply, however, an ability by the producer to learn which climate scenario is occurring by observing water supply in the first year. Producers are not currently able to resolve climate change uncertainty that quickly. Of course the assumption in our DSSP model that producers learn nothing about climate change over a three-year period might also be unrealistic. Additional research is needed to refine the treatment of learning in our DSSP model and strike a better balance between these two extreme assumptions.
2. Note that if we calculate expected profit using subsets of the optimal solution, we must also use the appropriate climate scenario's original probabilities, rather than the joint probabilities used in the weather/climate uncertainty model.
3. Prior to knowledge of which climate change scenario will occur, both estimates indicate a 10 per cent

decline in expected profit. The DSSP model that assumes weather uncertainty but climate certainty has no equivalent prediction. We can approximate, however, by calculating the weighted average of expected profit under 'increased EV' and 'decreased EV', which is expected profit under the 'wait-and-see' solution. Given a 50 per cent chance of 'increased EV' (which imposes a 3 per cent decline in expected profit), and a 50 per cent chance of 'decreased EV' (which imposes a 13 per cent decline), an 8 per cent decline in expected profit is predicted before complete information about climate change becomes available.

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7 Using panel data models to estimate the economic impacts of climate change on agriculture

Olivier Deschenes and Michael Greenstone

INTRODUCTION

Agriculture is one of the economic sectors most sensitive to weather fluctuations and extreme events since temperature and precipitation are direct inputs in agricultural production. As a result, there have been long-standing concerns and debates about the likely effects of global climate change on the agricultural sector in the USA and elsewhere.¹ Despite this massive research effort, there remains considerable uncertainty about the sign and magnitude of the likely effect of climate change on the US agricultural sector.

In this chapter, we review the emerging literature that has used panel data methods to estimate the economic impacts of climate change on agriculture. The focus is on methods relying on interannual variation in weather as the primary source of identification for the statistical models, as in Deschenes and Greenstone (2007), Kelly et al. (2005), Guiteras (2009) and Schlenker and Roberts (2009).²

In the third section we present a simple conceptual framework that emphasizes the strengths and weaknesses of approaches that rely on interannual variation in temperature and precipitation distributions to identify their effects on farm productivity, as well as guiding its interpretation. The key point is that the approach's primary limitation is that farmers cannot implement the full range of adaptations in response to a single year's weather realization whereas they could do so in response to a more permanent change. As such, relying on short-term variation to infer long-run responses may overstate the damage associated with climate change.

We make use of detailed high-frequency weather data and economic data from the 1987–2007 US Census of Agriculture and discuss the recent trends in agricultural outcomes and weather in the USA. We examine variation in farm profitability and growing-season weather both over time and across US counties (fourth section).

We then present empirical estimates of the effect of growing-season temperature and precipitation fluctuations on farm profits per acre of farmland. The preferred specification is based on panel data models that include fixed effect for counties and state*year, as well as controls for soil characteristics. Thus the weather parameters are identified from the county-specific deviations in weather about the county averages after adjustment for shocks common to all counties in a state. The county fixed effects control for all time-invariant, county-specific determinants of farm productivity, while the state*year effects effectively control for input and output prices that can vary geographically at a local level.³

We extend the previous work of Schlenker et al. (2006) and Deschenes and Greenstone (2007) that modeled the effect of growing season temperature through cumulative heating degree-days. Rather here we model temperature through a series of temperature-day

bins that span the whole growing-season distribution and allow for nonlinear effects of temperature within the growing season. The main finding is that there is an inverted-U-shaped relationship between farm productivity and growing-season temperature-days: relatively cold and hot growing-season temperature-days are associated with reductions in profits per acre, although the effects are generally statistically insignificant. We also perform a thorough sensitivity analysis and probe the extent of geographical differences in the estimate's relationship between profits and growing-season weather.

Finally, we combine climate change prediction from the National Centre for Atmospheric Research's (NCAR's) Community Climate Systems Model, version 3.0 (CCSM3) scenario A2 with our historical estimates to produce estimates of the likely impact of climate change on US agricultural profits. With this approach, climate change is projected to have a negative but modest impact on agricultural profits at the end of the century. This impact is smaller in econometric models that allow for local shocks to input and output prices and productivity. Across four specifications, the present discounted value (PDV) of projected annual impacts over the remainder of the century is roughly US\$28 billion, which is slightly less than the average annual aggregate profits in the US agricultural sector. In addition, it is worth highlighting that all of these estimates are derived under the unrealistic assumption of no technological progress and adaptation over the remainder of the century. It seems reasonable to assume these economic forces will contribute to reducing the predicted damages. As such, we view this evidence as an indication that the case for large negative impacts of climate change on aggregate profits in the US agricultural sector is limited.

CONCEPTUAL FRAMEWORK

Assessing the likely impact of climate change on the agricultural sector requires credible estimates of the relationship between agricultural outcomes (such as farm profits or land values) and weather and/or climate inputs. Once a credible relationship is estimated, it is relatively straightforward to project the likely effect of climate change, although this requires important and strong assumptions that we discuss below. Notably, the relationship between weather, climate inputs and agricultural outcomes is likely to vary across and within the country, reflecting differences in climate, farming practices, access to technology and local input and output market conditions.

The different methodologies that have been used to estimate the consequences of global climate change for the agricultural sector in the USA and in other countries can be classified in three broad categories: the integrated assessment model (IAM) approach (sometimes called the 'production function' approach); the hedonic (or Ricardian) approach, and, more recently, the approach proposed by Deschenes and Greenstone (2007) and Kelly et al. (2005) that relies on interannual fluctuations in weather and farm profits to infer the impacts of climate change. In this section we present the conceptual framework underlying the last approach since the others are discussed elsewhere in this *Handbook*.

In an influential paper, Mendelsohn et al. (1994) proposed a hedonic approach as a solution to the problem that the production function approach ignores, which is the possibility of adaptation by farmers. The hedonic method aims to measure the impact

of climate change by directly estimating the effect of temperature and precipitation on the value of agricultural land. Its appeal is that if land markets are operating properly, prices will reflect the PDV of land rents into the infinite future, therefore accounting for possible substitution across land usage. Thus the hedonic approach promises an estimate of the effect of climate change that accounts for the compensatory behavior that undermines the production function approach.

However, to successfully implement the hedonic approach it is necessary to obtain consistent estimates of the independent influence of climate on land values, and this requires that all unobserved determinants of land values are orthogonal to climate. Deschenes and Greenstone (2007) demonstrated that temperature and precipitation normals (i.e. measures of climate) covary with soil characteristics, population density, per capita income and latitude. Moreover, Schlenker et al. (2006) show that the availability of irrigated water also covaries with climate. This means that functional form assumptions are important in the hedonic approach and may imply that unobserved variables are likely to covary with climate. Furthermore, recent research has found that cross-sectional hedonic equations appear to be plagued by omitted-variables bias in a variety of settings (Black, 1999; Black and Kneisner, 2003; Chay and Greenstone, 2005; Greenstone and Gallagher, 2008). Overall, it may be reasonable to assume that the cross-sectional hedonic approach confounds the effect of climate with other factors (e.g. soil quality).

Using Annual Variation in Weather to Infer the Impacts of Climate Change

Deschenes and Greenstone (2007) (henceforth DG) and Kelly et al. (2005) proposed an alternative strategy to estimate the effects of climate change.⁴ The basic idea is to use panel data with repeated observations on agricultural outcomes for the same geographical unit over time. The key aspect of this method is that the weather parameters are identified from annual random shocks to the weather distribution for each geographical unit.

For example, DG used a county-level panel data file constructed from the 1987–2002 US Census of Agriculture to estimate the effect of weather on agricultural profits, conditional on county and state by year fixed effects. In that case, identification comes from the county-specific deviations in weather about the county averages after adjustment for shocks common to all counties in a state. This variation is presumed to be orthogonal to unobserved determinants of agricultural profits, so it offers a possible solution to the omitted-variables bias problems that appear to plague the hedonic approach. In the empirical analysis below, we extend the DG analysis by employing more recent data from the 2007 Census of Agriculture, and by incorporating insights from recent research on the relationship between crop yields and growing-season weather.

The DG approach differs from the hedonic approach in a few key ways. First, under the assumption of additive separability, its estimated parameters are purged of the influence of all unobserved time-invariant factors. Second, it is not feasible to use land values as the dependent variable once the county fixed effects are included. This is because land values reflect long-run averages of weather, not annual deviations from these averages, and there is no time variation in such variables. Third, although the dependent variable is not land values, our approach can be used to approximate the effect of climate change

on agricultural land values. Specifically, we estimate how farm profits are affected by increases in temperature and precipitation. We then multiply these estimates by the predicted changes in climate to infer the impact on profits. Since the value of land is equal to the present discounted stream of rental rates, it is straightforward to calculate the change in land values when we assume that the predicted change in profits is permanent and make an assumption about the discount rate.

The Economics of Using Annual Variation in Weather to Infer the Impacts of Climate Change

There are two economic issues that could undermine the validity of using the relationship between short-run variation in weather and farm profits to infer the effects of climate change. The first issue is that short-run variation in weather may lead to temporary changes in prices that obscure the true long-run impact of climate change. To see this, consider the following simplified expression for the profits (π) of a representative farmer who is producing a given crop (and is unable to switch crops in response to short-run variation in weather):

$$\pi = p(q(w)) q(w) - c(q(w)) \quad (7.1)$$

where p , q , and c denote prices, quantities and costs, respectively. Prices and total costs are a function of quantities. Importantly, quantities are a function of weather, w , because precipitation and temperature directly affect yields and possibly livestock.

Since climate change is expected to lead to a permanent change in climate, we would like to isolate the long-run change in profits. Consider how the representative producer's profits respond to a change in weather:

$$\partial \pi / \partial w = (\partial p / \partial q) (\partial q / \partial w) q + (p - \partial c / \partial q) (\partial q / \partial w) \quad (7.2)$$

The first term is the change in prices due to the weather shock (through weather's effect on quantities) multiplied by the initial level of quantities. When the change in weather affects output, the first term is likely to differ in the short and long runs. Consider a weather shock that reduces output (e.g. $\partial q / \partial w < 0$). In the short run supply is likely to be inelastic due to the lag between planting and harvests, so $(\partial p / \partial q)_{SR} < 0$. This increase in prices helps to mitigate the representative farmer's losses due to the lower production. However, the supply of agricultural goods is more elastic in the long run as other farmers (or even new farmers) will respond to the price change by increasing output. Consequently, it is sensible to assume that $(\partial p / \partial q)_{LR} > (\partial p / \partial q)_{SR}$ and is perhaps even equal to zero. The result is that the first term may be positive in the short run, but small or zero in the long run.

The second term in equation (7.2) is the difference between price and marginal cost multiplied by the change in quantities due to the change in weather. This term measures the change in profits due to the weather-induced change in quantities. It is the long-run effect of climate change on agricultural profits (holding constant crop choice), and this is the term recent studies have been trying to estimate credibly. Although the DG empirical approach relies on short-run variation in weather, there are several reasons that it may

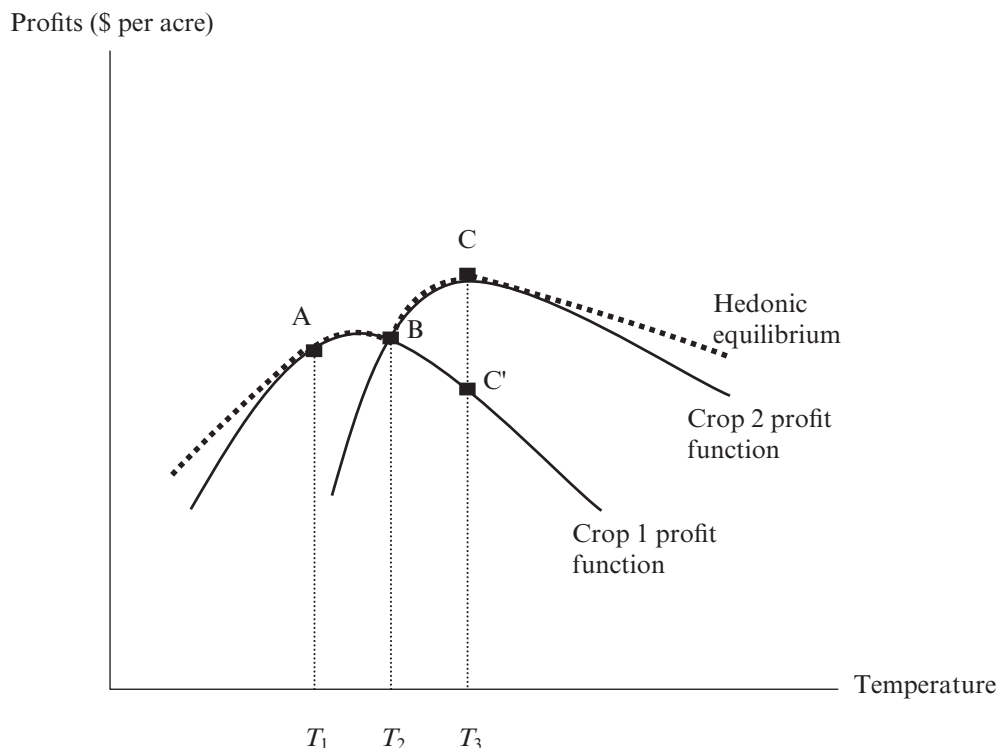


Figure 7.1 *Theoretical relationship between agricultural profits and growing-season temperature*

be reasonable to assume that our estimates are largely purged of the influence of price changes (i.e. the first term in equation (7.2)). The preferred econometric model proposed by DG includes a full set of state*year interactions, so it non-parametrically adjusts for all factors that are common across counties within a state by year, such as crop price levels. Thus the estimates will not be influenced by changes in state-level agricultural prices, or more generally by local shocks to productivity, input prices and output prices. Since the inclusion of state*year effects is demanding of the data and absorbs a large amount of variation in weather, we also consider other specifications that allow year effects by US Census Division and by USDA regions in the analysis below.

The second potential threat to the validity of our approach is that farmers cannot undertake the full range of adaptations in response to a single year's weather realization. Specifically, permanent climate change might cause them to alter the activities they conduct on their land. For example, they might switch crops because profits would be higher with an alternative crop.

Figure 7.1 illustrates this issue where farmers can choose between two crops only. Profits per acre are on the y axis and temperature is on the x axis. For simplicity, we assume that the influence of precipitation and all other exogenous determinants (e.g. soil quality) of profits per acre have been successfully controlled or adjusted for. The

Crop 1 and Crop 2 profit functions reveal the relationship between profits per acre and temperature when these crops are chosen. It is evident that crop-specific profits vary with temperature. Furthermore, the profit-maximizing crop varies with temperature. For example, Crop 1 maximizes profits between T_1 and T_2 , Crops 1 and 2 produce identical profits at T_2 where the profit functions cross (i.e. point B), and Crop 2 is optimal at temperatures between T_2 and T_3 .

The hedonic equilibrium is denoted as the broken line and it represents the equilibrium relationship between temperature and profits. In the long run, when farmers can freely switch crops (and more generally between all types of farming activities), they will choose to operate along the hedonic equilibrium because it reveals the crop choices that maximize their profits. It is formed by the regions of each crop's profit function where that crop produces the highest profits over all potential uses of that land.

Now consider a permanent increase in temperature from T_1 to T_3 . If farmers are able to switch production from Crop 1 to Crop 2, then their profits can be read off the y axis at point C. However, farmers who are unable to switch crops will earn profits associated with point C'. Thus the long-run change in profits is $C - A$, but in the short run, the difference is $C' - A$, which is a downward-biased estimate of the long-run effect. It is noteworthy that if the new temperature is $\geq T_1$ and $\leq T_2$, then the farmer's short-run and long-run profits are equal because the hedonic equilibrium and the Crop 1 profit function are identical.

The empirical strategy proposed by DG relies on year-to-year variation in weather and thus it is unlikely that farmers are able to switch crops upon a year's weather realization. The import for applications of this method is that its estimates may overstate the damage associated with climate change relative to the preferred long-run effect that allows for all economic substitutions. If the degree of climate change is 'small' (i.e. between T_1 and T_2 in Figure 7.1), however, our estimates are equal to the preferred long-run effect. Finally, while the full range of adaptations is not available to farmers in the short run, we note that in response to year-to-year fluctuations in weather, farmers are able to make some adjustments. For example, farmers can adjust their mix of inputs in response to a short-run shock (e.g. fertilizer and irrigated water usage), so the subsequent estimates do account for some degree of adaptation.

DATA SOURCES AND SUMMARY STATISTICS

To implement the analysis, we collected the detailed and comprehensive data available on agricultural production, temperature, precipitation and soil quality. This section describes these data and reports some summary statistics.

Census of Agriculture Data

The data on agricultural finances are from the 1987, 1992, 1997, 2002 and 2007 Censuses of Agriculture. Data for years prior to 1987 are available; however, these data are not useful for the purpose of this chapter since production expenditure variables are not consistently available. By law, all farms and ranches from which \$1000 or more of agricultural products are produced and sold, or normally would have been sold during the

Census year, are required to submit a census form. For confidentiality reasons counties are the finest geographic unit of observation that is publicly available in the Census of Agriculture.

From these data we construct a county-level measure of agricultural profits per acre of farmland. The numerator is constructed as the difference between the market value of agricultural products sold and total production expenses across all farms in a county. The revenues component measures the gross market value before taxes of all agricultural products sold or removed from the farm during the Census year, regardless of who received the payment, and the year of production. Importantly, it does not include income from participation in federal farm programs,⁵ labor earnings off the farm (e.g. income from harvesting a different field), or nonfarm sources. As such, it is a measure of the revenue produced with the land.

Total production expenses are the measure of costs. They include expenditures by landowners, contractors and partners in the operation of the farm business. This covers all variable costs such as those for seeds, labor, agricultural chemicals/fertilizers and energy. It also includes measures of interest paid on debts and the amount spent on repair and maintenance of buildings, motor vehicles and farm equipment used for farm business. The main limitation of the production expenditure variables in the Census of Agriculture is that it does not account for the rental rate of the portion of the capital stock that is not secured by a loan, so it is only a partial measure of farms' cost of capital. In addition, changes in inventory values are not accounted for. Consequently, the farm profits variable should be interpreted with caution. Similar to the revenue variable, the measure of expenses is limited to those that are incurred in the operation of the farm, so, for example, any expenses associated with contract work for other farms are excluded.

Another noteworthy issue regarding the farm profit variable is that the Census of Agriculture defines revenues as the sales of agriculture products in a calendar year, irrespective of the year of production.⁶ Since farmers may engage in inventory management decisions that allow them to smooth their income across years, it is important to derive a profit measure that accounts for this optimal storage behavior. Since it is based on revenues from the sales of agriculture products by calendar year and irrespective of the year of production, the farm profit measure derived from the Census of Agriculture embodies optimal storage decisions.

In practice this means that, for example, a bushel of corn that is stored this year will be sold in a subsequent year. Analogously, drawing down inventories this year will reduce the crops available for sale in future years. The point is that the full impact of a weather realization on profits can only be observed over periods longer than a year because inventory decisions allow farmers to spread the impacts over several years. This compensatory behavior suggests that measures of profits, which include revenues from sales of products regardless of their date of production, should be determined by current and lagged weather variables. The inclusion of lagged weather variables is necessary because the quantities that a farmer sells in a given year are affected by the full history of weather realizations through her storage decisions.

More generally, the structural relationship between storage decisions and weather realizations is a complicated process. It depends on several factors, including the weather realization's expected impact on current and future crop prices, storage costs, the length of time before a crop can be stored without spoiling and the interest rate. A careful

examination of this behavior would require a long panel data set with detailed information on farmer behavior. Such an analysis is beyond the scope of this chapter. Deschenes and Greenstone (2011a) report simple dynamic estimates of the effects of weather shocks on farm profits.

Historical Weather Data

The weather data are drawn from the National Climatic Data Center (NCDC) Summary of the Day Data (File TD-3200). The key variables for our analysis are the daily maximum and minimum temperature as well as the total daily precipitation. For most parts of this chapter, we follow the convention in the literature and focus on the daily mean temperature, which is the simple average of the maximum and minimum. We also examine the effect of minimum and maximum temperature separately.⁷

To ensure the accuracy of the weather readings, we use a simple rule to select the weather stations.⁸ In any given year, we select stations that operated continuously for that year and, consequently, stations can move in and out of the sample across the year.⁹ The acceptable station-level data are then aggregated at the county level by taking an inverse-distance weighted average of all the valid measurements from stations that are located within a 200 km radius of each county's centroid. The valid measurements from acceptable stations are weighted by the inverse of their squared distance to the centroid so that more distant stations are given less weight.

We follow two approaches from the recent literature. First, we convert daily temperatures into degree-days, which represent cumulative heating units (see, e.g., Schlenker et al., 2006; Deschenes and Greenstone, 2007). This is motivated by the agronomic research that has shown that plant growth depends on the cumulative exposure to heat and precipitation during the growing season (Hodges, 1991; Grierson, 2002). The effect of heat accumulation is nonlinear, as temperature must be above a threshold and below a ceiling for plants to absorb heat; plants cannot absorb extra heat when temperature is too high. These thresholds or bases are likely to vary across crops and perhaps growing area, but we follow Schlenker et al.'s (2006) application of Ritchie and NeSmith's (1991) suggested characterization for the entire agricultural sector, and use a base of 46°F and a ceiling of 90°F (or roughly 8 ° and 32 °C).

We use daily-level data on temperatures and calculate growing-season degree-days between 1 April and 30 September, which covers the growing season for most crops except winter wheat (US Department of Agriculture, NASS, 1997). The growing-season degree-day variable is then calculated by summing the daily measures over the entire growing season.¹⁰ Similarly, we sum all precipitation during the growing season.

Our preferred specification is based on models where exposure to growing-season temperature is characterized by an exhaustive list of temperature-days categories or 'bins' that span over the whole daily temperature distribution (see, e.g., Deschenes and Greenstone, 2011b; Deschenes et al., 2009). The main advantage of this modeling is that it allows for nonlinearities in the temperature effects within the growing season, whereas the degree-days approach does not. For example, consider a plot of farmland where the average daily temperature is always 70°F for a 30-day month. Based on the definition above, this would produce 720 degree-days. On the other hand, consider the same plot of land, but exposed to 21 days of 70°F daily average temperature and nine days of 120°F

daily average temperature, for an exposure to 750 degree-days. Clearly, plant growth and eventually farm profits would be very differently affected by those two exposures. Thus the binning of the data, which preserves the daily variation in temperatures, is important because of the potential for substantial nonlinearities in the relationship between agricultural productivity and temperature. This is also important since the functional form of the relationship between agricultural profits and weather is *a priori* unknown.

Climate Change Prediction Data

Climate predictions are obtained from NCAR'S CCSM3 which is a coupled atmospheric-ocean general circulation model (NCAR 2007). This model is considered state of the art and was used in the Fourth Assessment Report by the International Panel on Climate Change (IPCC, 2007). Predictions of climate change from both this and other models are available for several emission scenarios, corresponding to 'storylines' describing the way the world (population, economies etc.) may develop over the next 100 years. We focus on the A2 scenario, a 'business-as-usual' scenario that is the proper baseline scenario to consider when evaluating policies to restrict greenhouse gas emissions. As such, predictions from the A2 scenario feature some of the largest predicted increases in global temperature.

We use inverse-distance weighted averages to assign grid point predictions to counties in the same manner as the station-level weather data are processed. All grid points located in a prespecified radius of a county's centroid are used to impute the climate prediction, with measurements from grid points located further away from the centroid receiving less weight. A radius of 200 km ensures that every county gets a valid Hadley 2 and CCSM3 A2 prediction for every day between 2010 and 2099. From these daily grid-point-level data we construct the same measures of growing-season degree-days, total rainfall and temperature-day bins we defined on the historical weather data. From these, we defined our measures of predicted climate change for any county-year over 2010–99 as the difference between the Hadley 2/CCSM3 model-predicted growing-season weather for a given county-year, and the 1970–2000 average of the same growing-season weather variable for that county.¹¹

PROFITS, GROWING-SEASON WEATHER AND PREDICTED CLIMATE CHANGE IN US AGRICULTURE

The top panel of Table 7.1 reports county-level averages for the key variables in the Census of Agriculture 1987, 1992, 1997, 2002 and 2007. Unless noted otherwise, we focus on a balanced sample of 2256 counties with valid information in each Census year. Over the period, the number of farms per county varied between 688 and 793. The total number of acres devoted to farming declined from 346 000 to 331 000 acres per county, or by roughly 4 per cent. Similarly, the acreage devoted to cropland declined by 9 per cent, from 148 000 to 144 000 acres per county on average. Irrigated acres increased from 20 000 to 25 000 acres per county.

Panel 2 reports farm profits information. We focus on 1987–2007, since complete data on profits are only available for these five censuses.¹² During this period the mean

Table 7.1 County-levels summary statistics on US farming sector

	1987	1992	1997	2002	2007
1. Farms and farmland acreage					
Number of farms	747.5	690.3	687.5	769.5	792.6
Total land in farms (1000 acres)	345.9	338.6	334.5	337.0	331.4
Total cropland (1000 acres)	157.8	155.7	153.9	154.9	144.4
Irrigated farmland	20.0	21.4	23.9	24.0	24.5
2. Farm sales, expenditures and profits					
Total farm sales (\$mil.)	82.8	84.2	92.4	86.7	110.0
Total farm expenditures (\$mil.)	66.2	68.1	71.1	75.1	89.9
Profits (\$mil.)	16.6	16.1	21.3	11.6	20.1
Profits per acre (\$/acre)	47.9	47.6	63.8	34.4	60.6
Std dev. profits per acre (\$/acre)	69.3	67.4	101.2	93.9	112.3
3. Other sources of farm revenues					
Total government payments (\$mil.)	5.3	2.5	2.1	2.6	2.7
4. Growing-season weather					
Degree-days (base 46 °F, Ceiling 90 °F)	3945.7	3584.3	3706.2	4024.9	3998.5
Days with mean temperature < 40 °F	6.9	9.5	12.7	12.2	11.1
Days with mean temperature > 80 °F	23.9	16.3	22.7	30.9	24.4
Total precipitation	15.4	16.4	17.1	14.8	17.5

Notes: All dollar figures in 2005 constant dollars. There are 2256 counties in the balanced sample, for a total of 11 280 county-year observations. Means of farm profits per acre and growing-season weather variables are weighted by acres of farmland.

county-level sales of agricultural products ranged from \$83 to \$110 million (2005 constant dollars). Average farm production expenses grew from \$66 to \$90 million. The mean county profits from farming operations ranged from \$11.6 million in 2002 to \$21.3 million in 1997. Profits per acre of farmland followed a similar trend, ranging from \$34.4 per acre to \$63.8 per acre.¹³ Another notable aspect of the overall increase is the variability of farm profits across counties. This is shown by the standard deviation of farm profits per acre, which increased by about 40 per cent from 1987 to 2007. Finally, it is worthwhile to emphasize that these profit figures do not include government payments, which are listed in row 3. Notably, government transfers decreased by about half after 1987. The subsequent analysis of profits also excludes government payments.

The final panel reports summary statistics on agricultural growing-season weather. Unless noted otherwise, the growing season is defined as from April to September. The precipitation variables are measured in inches. The degree-day variables are reported in °F. We also report the number of days in the growing season where average daily temperatures exceed 80 °F or are less than 45 °F. These correspond to the two extremes of the growing-season daily temperature distribution, and the incidence of such temperature-days may have detrimental effects on farm profits. Figure 7.3 displays the whole growing-season daily temperature distribution.

Across the five years, average growing-season degree-days is around 4000, with 1992 and 1997 distinctively being below this average. Average growing-season precipitation

is approximately 17 inches, with 1987 and 2002 being the two driest years in this sample. In the typical sample year there are 7–13 days where the mean temperature is lower than 45°F and 16–31 days where the mean temperature exceeds 80°F, out of a possible 183 days. Overall, the national means of these variables are relatively stable over time and do not exhibit a clear trend. As Table 7.2 documents, geographical variation in average growing-season degree-days and rainfall is significantly more important than the time-series variation in the national means.

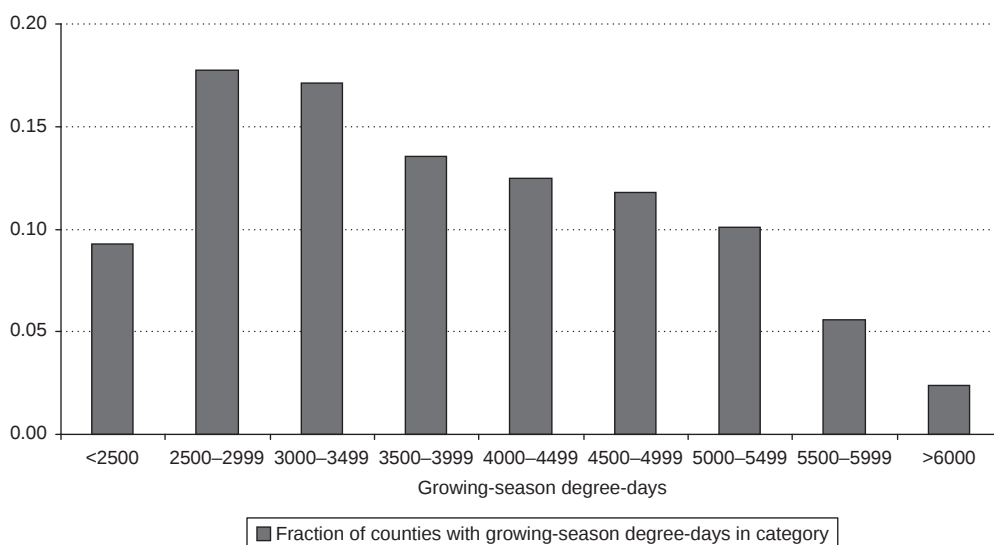
Figure 7.2 reports histograms on growing season degree-days (A) and precipitation (B). These statistics are calculated as the mean over the five sample years, and weighted by acres of farmland for each county-year. The distribution of growing-season degree-days is right skewed, with roughly 50 per cent of counties receiving between 2500 and 4000 degree-days. At the upper tail, less than 5 per cent of counties are exposed to 6000 or more growing-season degree-days. The distribution of growing-season precipitation appears more symmetric. The modal category is 15–20 inches of rainfall, and accounts for 22 per cent of counties.

The pale bars in Figure 7.3 depict the distribution of growing-season daily mean temperatures across ten temperature categories or bins, again during the 1987–2007 period. These categories represent daily mean temperature less than 40°F, greater than 85°F, and the nine 5°F wide bins in between. The height of each light-colored bar corresponds to the mean number of growing-season days that the average farming county experiences in each bin; this is calculated as the weighted average across county-by-growing season realizations, where the county-by-year's acreage of farmland is the weight. The average number of days in the modal bin of 70 – 75°F is 30. The mean number of days at the endpoints is 5.6 for the less than 40°F bin and 4.8 for the greater than 85°F bin. These relevant bins form the basis for our semi-parametric modeling of temperature in equations for agricultural profits throughout the remainder of this chapter, although we also consider some estimates based on models for degree-days.

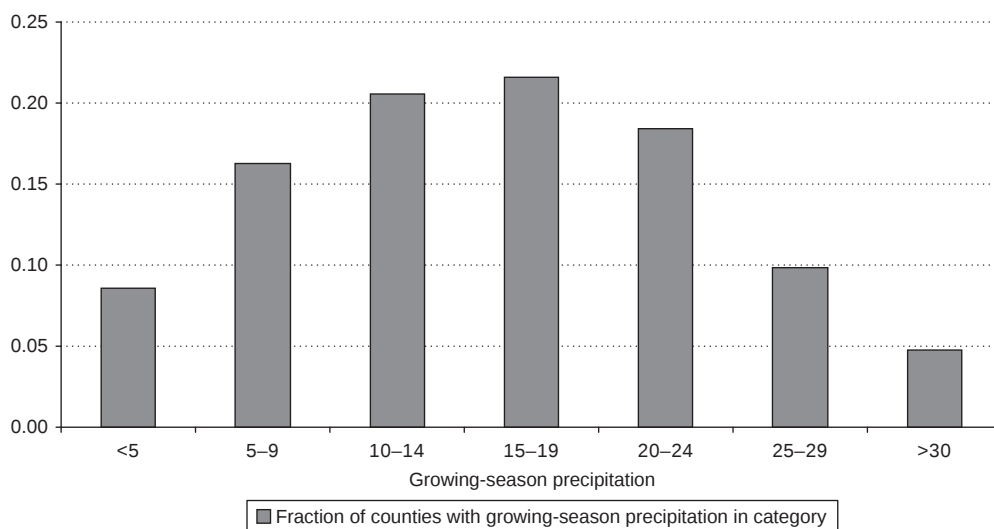
Figure 7.3 also provides an opportunity to understand how the full distributions of daily mean temperatures are expected to change under the CCSM3 A2 model. The dark bars report the change in the number of days in each temperature category that the average farmland is expected to experience. This calculation assumes that the geographical distribution of farmland acreage remains at the 1987–2007 historical baseline. The most important change in the distribution is the upper bin. The CCSM3 A2 predictions indicate that, by the end of the century, the average farm will experience 43.7 *additional* days per growing season where the mean daily temperature is in excess of 85°F. Recall that the historical average for this temperature category is 4.6, so CCSM3 A2 predicts an almost tenfold increase in high-temperature growing-season days by the end of the century.

This increase in the incidence of high average temperature days is offset by a decrease in the number of lower average temperature days during the growing season. The incidence of days with mean temperature lower than 75°F is predicted to decrease by about 53 days during the growing-season. An examination of the remainder of the figure highlights that the reduction in cold growing-season days (less than 40°F) is much smaller than the increase in extreme hot growing-season days (more than 80°F). The subsequent analysis demonstrates that this has a profound effect on the estimated impacts of climate change on agricultural productivity.

(A) Growing-season degree-days

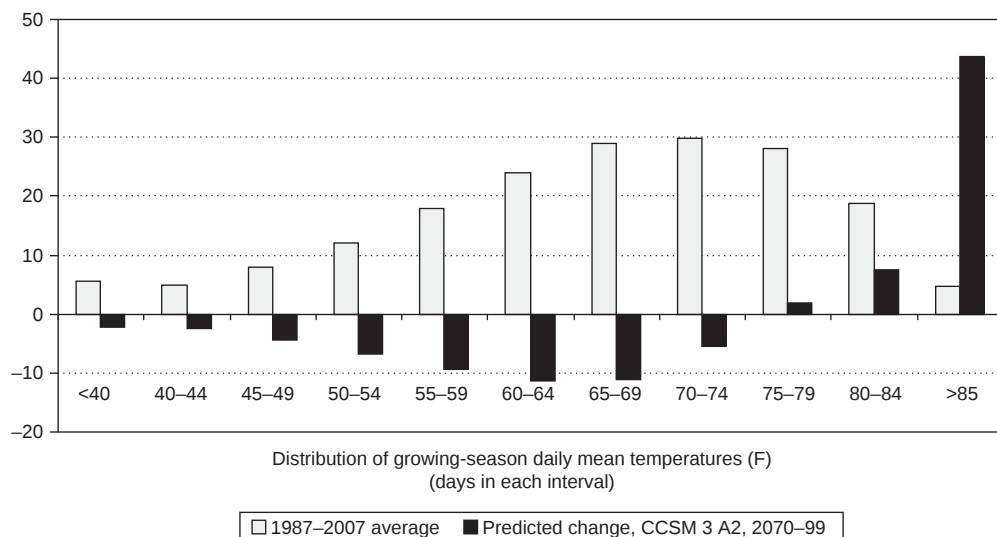


(B) Growing-season precipitation



Notes: Sample: 2256 counties (total observations = 11 280 county-year observations). The bars represent the fraction of counties in each degree-day and precipitation category, weighted by acres of farmland. Degree-day defined with a base of 46.4°F and a ceiling of 89.6°F. Growing season defined as April to September. See the text for more details.

Figure 7.2 Distribution of growing-season degree-days and precipitation, 1987–2007



Notes: The pale bars represent the average number of days per growing season in each temperature category over 1987–2007, weighted by acres of farmland. The darker bars represent the model-predicted change in the average number of days per growing season in each temperature category. Changes are defined as the difference between the 1987–2007 average in each category and the 2070–99 predicted average number of days in each category. Predicted changes are weighted by the average farmland acreage over 1987–2007 in each county. See the text for more details.

Figure 7.3 Distribution of growing season daily mean temperatures (°F), 1987–2007, and predicted changes in distribution growing-season daily mean temperatures according to CCSM3 A2

Table 7.2 examines the geographical variation in farm profits, growing-season degree-days and precipitation (calculated as the mean over the five sample years), and predicted changes in growing-season degree-days and precipitations according to the CCSM3 A2 model. For brevity, these predicted changes are computed as the difference between the predicted average over 2070–99 and the 1970–2000 historical average. All statistics are weighted by the 1987–2007 average in farmland acres for each county and are reported as national average (column 1) and the specific average for each of the nine US Census divisions in order to display the geographical variation (columns 2–10).

Panel A reports average farm profits per acre calculated from the 1987–2007 Census of Agriculture. The national average is \$50.8 per acre with a standard deviation of 91. As shown in columns 2 to 10, there is substantial geographical variation across US Census divisions, and the most profitable agricultural land is interspersed throughout the country rather than being clustered in a few specific areas. The Middle Atlantic, South Atlantic and Pacific divisions are the three most profitable ones, with profits in excess of \$120 per acre. At the other end of the distribution are West South Central and Mountain, with farm profits of less than \$25 per acre, and so the gap between the most and least profitable areas is almost a factor of five.

Panel B reports growing-season degree-days and precipitation, averaged over the 1970–2000 period. The national average (weighted by acres of farmland) is about

Table 7.2 Average farm profits, growing-season weather and predicted changes in growing-season weather, by US Census division

	All Counties	By Census division							
		New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain Pacific
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(A) Average farm profits per acre	50.8	119.6	122.3	98.0	45.1	129.0	62.9	25.1	14.9
Std dev.	(90.9)	(160.3)	(143.5)	(66.9)	(47.9)	(166.0)	(84.0)	(44.7)	(47.0)
(B) Historical weather data (1970–2000)									
Growing-season degree-days	3825.3	2573.8	3021.1	3352.3	3497.1	4907.9	4581.3	5294.7	3015.9
Std dev.	(1127.1)	(311.5)	(374.5)	(465.2)	(630.8)	(784.2)	(501.8)	(553.2)	(840.6)
Growing-season temperature-days < 45 °F	11.3	23.6	16.3	13.8	14.7	1.8	2.7	1.2	18.4
Std dev.	(9.8)	(6.2)	(5.8)	(5.9)	(7.6)	(2.5)	(2.0)	(1.5)	(9.6)
Growing-season temperature-days > 80 °F	25.2	1.4	3.3	7.8	15.6	43.7	28.7	66.5	8.0
Std dev.	(29.3)	(1.1)	(3.1)	(5.9)	(12.4)	(30.0)	(18.6)	(25.5)	(16.6)
Growing-season precipitation	16.3	23.3	23.2	22.6	18.2	27.2	26.1	18.7	9.5
Std dev.	(7.2)	(1.4)	(1.6)	(1.6)	(4.3)	(4.3)	(1.6)	(5.0)	(2.4)
(C) Predicted change, CCSM 3 A2, 2070–99									
Growing-season degree-days	1438.7	1133.8	1488.0	1977.0	1773.2	1082.4	1671.1	1101.6	1365.3
Std dev.	(486.7)	(206.6)	(228.3)	(207.3)	(272.9)	(400.6)	(227.9)	(377.2)	(408.5)
Growing-season temperature-days < 45 °F	-8.9	-4.6	-11.8	-10.2	-9.6	-9.7	-1.3	-2.2	-0.9
Std dev.	(8.1)	(5.9)	(2.5)	(3.5)	(3.5)	(4.5)	(1.9)	(1.5)	(1.0)
Growing-season temperature-days > 80 °F	51.2	14.0	33.8	67.6	58.7	55.5	81.6	44.3	45.0
Std dev.	(20.5)	(5.4)	(10.3)	(16.8)	(14.1)	(13.5)	(7.5)	(19.8)	(17.4)
Growing-season precipitation	0.0	-2.5	-2.9	-4.7	-0.4	0.9	-4.3	0.5	1.9
Std dev.	(4.9)	(1.4)	(1.6)	(2.2)	(5.1)	(7.5)	(2.3)	(5.6)	(3.5)

Notes: Statistics based on balanced sample of 2256 counties. Averages are weighted by farmland acres in a given year (Panel A) or the average farmland acres over 1987–2007 (Panels B and C). Predicted change defined as difference between 2070–99 average and 1970–2000 average. See the text for more details. States included in each Census division: New England (CT, ME, MA, NH, RI, VT), Middle Atlantic (NJ, NY, PA), East North Central (IN, IL, MI, OH, WI), West North Central (IA, KS, MN, MO, NE, ND, SD), South Atlantic (DE, DC, FL, GA, MD, NC, SC, VA, WV), East South Central (AL, KY, MS, TN), West South Central (AR, LA, OK, TX), Mountain (AZ, CO, ID, NM, MT, UT, NV, WY), Pacific (CA, OR, WA).

3800 degree-days and 16 inches of rainfall. Once again, geographical variation in these variables is evident in columns 2 to 10, with the South Atlantic and West South Central divisions being the 'warmest' and New England and Middle Atlantic being the coldest. South Atlantic and East South Central receive the most rain and Mountain and Pacific divisions receive the least rain. As is well known, farming in these western areas is driven to a large extent by irrigation and not rainfall. The geographical variation is also notable for the less than 45°F and more than 80°F growing season temperature days, with the South Atlantic and West South Central divisions having the highest incidence of >80°F temperature-days, and the New England and Mountain divisions having the highest incidence of <45°F temperature-days. The national averages of these variables are 11.3 and 25.2, respectively, which corresponds to six and 14 per cent of the total growing-season days.

Panel C of Table 7.2 reports on the predicted change in growing-season weather according to the CCSM3 A2 model and scenario. Changes are defined as the difference in the average 2070–99 predictions and the 1970–2000 historical averages. All the statistics are weighted by the average farm acreage between 1987 and 2007, so this implicitly assumes that the geographical distribution of farming practices and intensity will remain stable. Since farmers are likely to adapt to permanent climate change, the actual acreage-weighted distribution of growing-season weather by 2099 will very likely differ from the predictions reported in Table 7.2.

The CCSM3 A2 model predicts a mean increase in degree-days of roughly 1400 by the end of this century. This is a sizable increase, corresponding to about 40 per cent of the historical baseline average. This reflects the fact that the A2 scenario is one of those that predict the largest increase in temperature. Other families of scenarios such as B1 predict more modest increases in temperature. Columns 2 to 10 again document striking geographical differences, ranging from 1100 to 2000, where the southern divisions are predicted to experience the most dramatic increase in growing-season degree-days.

The next rows report the predicted change in the number of less than 45°F and more than 80°F growing-season temperature-days. Temperature-days less than 45°F are predicted to decrease by 4.6 days nationally, while temperature-days above 80°F are predicted to increase by 51 days, or 200 per cent of the historical baseline. This highlights that predicted climate change will not result in a uniform shift of the temperature distribution, at least not according to the CCSM3 A2 predictions. Similar to the geographical patterns highlighted for degree-days, there are sizable geographical differences in the predicted change in the daily temperature distribution. The model also predicts even greater intra-division variability in the increase in growing-season precipitation.

The main points of the preceding tables and figures are as follows: there does not appear to be a significant time trend in farm profits. Average farm profits per acre were highest in real terms in 1997 and 2007, and lowest in 2002. Similarly, there is little evidence of significant changes in average growing-season weather conditions over the period 1987–2007. Rather, geographical variation, documented here through differences across US Census divisions, appears to be the main source of variation for farm profitability, growing-season weather and the predicted changes in the distribution of growing-season weather. The implication of this is that predicted impacts of climate change on farm profits are likely to vary across areas of the country, and this is an issue we shall investigate in the empirical analysis below.

EMPIRICAL FRAMEWORK

The canonical estimating equation relating farm profits and growing-season weather is of the form

$$y_{ct} = \alpha_c + \lambda_t + X_{ct}\theta + \sum_{k=1}^K \beta_k W_{kct} + \varepsilon_{ct} \quad (7.3)$$

where the indices c and t denote county and year, respectively, and k represents different measures of weather (such as growing-season degree-days, number of days in various temperature bins or total precipitation). The dependent variable y_{ct} is expressed in dollars per acre of farmland, and converted into 2005 dollars. The empirical analysis will consider many possible specifications for the weather effects, including models that account explicitly for nonlinearities and dynamic relationships. In addition, we allow for the possibility that the effect of growing-season weather on profits varies across geographic areas. In this case, the parameters β will be allowed to vary across areas.

Equation (7.3) also includes a full set of county fixed effects, α_c . The appeal of including the county fixed effects is that they absorb all unobserved county-specific time-invariant determinants of the dependent variable. For example, to the extent that agricultural soil quality is constant over time, the county fixed effects will account for differences in soil quality across counties. As such, the inclusion of county fixed effects will help in mitigating the problem of omitted-variables bias that has plagued some of the previous literature. Variants of this approach have been used in Deschenes and Greenstone (2007) and Schlenker and Roberts (2009).

The model above also includes a full set of year fixed effects, λ_t , that control for annual differences in the dependent variable that are common across counties. Our preferred specifications below replace the year fixed effects with year effects that vary geographically to allow for local shocks to productivity, input prices and output prices. More specifically, we consider year effects specific to each of the nine USDA Farm Resource regions,¹⁴ year effects specific to each of the nine US Census divisions and state*year fixed effects as in DG (2007). The advantage of USDA-region and US Census division specific year effects is that they allow for regional shocks while preserving more variation in growing-season weather than the specification that includes state*year effects. An alternative is to directly control for prices as in Kelly et al. (2005). The variables in the vector X_{ct} are the soil quality variables we described earlier. These variables display very limited temporal variation, and their inclusion or exclusion does not change the estimates of the weather gradient conditional on the inclusion of the county fixed effects. Finally, the last term in equation (7.3), ε_{ct} , is a statistical error term.

The validity of any estimate of the impact of climate change based on equation (7.3) rests crucially on the assumption that its estimation will produce unbiased estimates of the β vector. Formally, the consistency of each β_k requires $E[W_{kct}\varepsilon_{ct} | X_{ct}, \alpha_c, \gamma_{rt}] = 0$. By conditioning on the county- and region-specific year fixed effects, the β_k s are identified from county-specific deviations in weather about the county averages after controlling for shocks common to all counties in a region. This variation is presumed to be orthogonal to unobserved determinants of agricultural profits, so it is unlikely to be confounded by omitted variables. A shortcoming of this approach is that all the fixed effects are likely

to magnify the importance of misspecification due to measurement error, which generally attenuates the estimated parameters.

Estimation

There are further issues about equation (7.3) that require attention. First, it is appropriate to estimate the equations using weights. Since the dependent variables are expressed in dollars per acres of farmland, there are two reasons to weight the models by the square root of acres of farmland. First, the estimates of the value of farmland from counties with large agricultural operations will be more precise than the estimates from counties with small operations, and this weight corrects for the heteroskedasticity associated with the differences in precision. Second, the weighted mean of the dependent variables will be equal to the mean value of farmland per acre in the USA. It is also likely that the error terms are serially correlated over time. To account for this, we present clustered standard errors, where the clusters are defined by counties. This allows for arbitrary serial correlation over time within counties.

Calculating the Predicted Impact of Climate Change on Farm Profits

Once the gradients of the profits functions are estimated, it is relatively straightforward to project the impacts of climate change. We simply combine the fixed-effect regressions estimates with the projected differences in growing-season weather from the CCSM3 A2 model (ΔW_{kc}). Summary statistics on these predicted changes were reported in Table 7.2 and Figure 7.3. The predicted impact on aggregate farm profits for county c is given by

$$IMPACT_c = ACRES_c \times \left(\sum_k \hat{\beta}_k \Delta W_{kc} \right) \quad (7.4)$$

where ΔW_{kc} is the predicted change in weather variable k in county c . These changes are specific to a climate change model, scenario and horizon (i.e. short-run, medium-run and long-run). The variables $ACRES_c$ represent the average acres of farmland during the sample period in county c . We need to ‘reweight’ the calculations since the regression models are profits per acre. Finally, to obtain the impact for the country as a whole, we simply sum the county-specific impacts ($IMPACT_c$) across counties. This can also be done at the sub-national level.

RESULTS

Estimates of the Relationship between Growing-season Weather and Farm Profits

This section reports estimates of the economic impact of climate change on agricultural profits based on the methods reported in the previous section. Figure 7.4 (see p. 248) presents our preferred estimates of the impact of the ten growing-season temperature-days bins on farm profits per acre. Specifically, it plots the estimated regression coefficients (i.e. the $\hat{\beta}_k$ s) from the estimation of equation (7.3), and where state*year

fixed effects are included to control for local price shocks. Since the number of days in a growing season sums to a constant (183), one of the $TMEAN_k$ variables needs to be normalized to zero. We dropped the 60–65°F bin, so each measures the estimated impact of an additional day in bin k on the farm profits per acre, relative to the impact of a day in the 60–65°F range. The figure also plots the estimated coefficients plus and minus two standard errors, so their precision is apparent.

It is evident that farm productivity is lowest at the lowest temperatures. For example, each day where the mean temperature is between 40 and 45°F is associated with a significant reduction of \$1 in profits per acre, relative to a day in the 60–65°F category. Conversely, each day where the mean temperature is between 55 and 60°F is associated with a significant increase of \$1 in profits per acre, relative to a day in the 60–65°F category. The evidence is less precise in the upper part of the daily temperature distribution. All estimated effects above the reference category are close to zero and none of the coefficients is bounded away from zero.

The nature of the estimated response function implies that a shift to the right in the daily temperature distribution will lead to increase in farm profitability (due to the reduction in the number of ‘cold’ days) at the same time as a decrease in farm profitability (due to the increase in the ‘hot’ days). The sign and magnitude of the net effect of warming due to climate change on farm profits will ultimately depend on which of the opposing effects dominates. This will be determined by the estimated response function (reported in Figure 7.4) and the predicted change in the daily temperature distribution (reported in Figure 7.3).

Table 7.3 reports the point estimates underlying the results in Figure 7.4 and corresponding to a quadratic specification based on growing-season degree-days. For compactness, we report the average effects in the lowest two (<40°F and 40–45°F) and highest two (80–85°F and >85°F) exposure bins, although all models include the 11 bins described earlier. These coefficients are shown in column 1a. Similarly, in column 1b we report the average effect of precipitation in the lowest two and highest two precipitation bins.¹⁵ In addition, in column 2 we also show estimates from a quadratic specification in growing-season degree-days and precipitation, as in Schlenker et al. (2006) and Deschenes and Greenstone (2007). For these variables, marginal effects evaluated at sample means are reported.

Examining first the temperature effects in the lowest and highest temperature categories, we note that both estimates are negative although asymmetric. Cold growing-season days lead to a reduction in profits per acre of roughly of \$0.02 per such day, compared to days in the reference category. Relatively hot growing-season days have little effect on profits per acre, with an average impact of $-\$0.0014$. In both cases, these estimates are not statistically different from zero. The evidence for precipitation is even less reliable: both reported estimates have relatively large standard errors. The lower panel displays p -values with F -statistics associated with the joint significance of the key variables in the model. The p -value on the 10 temperature-day bin variables is 0.001, indicating that these are important predictors of farm profits per acre. The p -value on the precipitation variable is 0.067, and so these variables appear to be a less significant predictor of farm profits per acre.

Column 2 displays the marginal effects from the quadratic models in degree-days and precipitation. The results suggest that a 100 degree-days increase would lead to \$0.44

Table 7.3 Baseline estimates of the effect of growing-season weather on farm profits per acre

	Model with temperature-day bins		Model with quadratics (2)
	Temperature (1a)	Precipitation (1b)	
Average effect in lowest 2 temperature categories	-0.0200 (0.0137)	0.1057 (0.3611)	-
Average effect in highest 2 temperature categories	-0.0014 (0.0319)	-0.0188 (0.4546)	-
Marginal effect of growing-season degree-days $\times$ 100	-	-	-0.4449 (0.7278)
Marginal effect of growing-season total precipitation	-	-	0.1728 (0.1726)
<i>P</i> -value for <i>F</i> -statistic on temperature bin / degree-day variables	0.001	-	0.821
<i>P</i> -value for <i>F</i> -statistic on precipitation variables	0.067	-	0.163
<i>P</i> -value for <i>F</i> -statistic on state*year effects	0.001	-	0.001
Observations	11 280		11 280
Soil controls	Yes		Yes
County fixed effects	Yes		Yes
State*year fixed effects	Yes		Yes

Notes: All dollar figures in 2005 constant dollars. Parameter estimates are from fixed effects models where the dependent variable is farm profit per acre; includes soil characteristics, county fixed effects, and state*year fixed effects. Standard errors are clustered by county. All models based on a balanced sample of 2256 counties. See the text for more details.

reduction in farm profits per acre, while each additional inch of growing-season rainfall increases farm profits by \$0.17 per acre. In both cases, the null hypothesis of zero effect cannot be rejected at the conventional level. One notable result in column 2 is that the p -values for growing-season degree-days and precipitation are all in excess of 0.16, suggesting that the weather effects, modeled as quadratics in total growing-season degree-days and rainfall, are jointly insignificant. Combined with the corresponding results in column 1a, we view this as evidence that the model with temperature and precipitation bins is better specified, and we mostly focus on this model for the rest of this chapter.

Table 7.4 reports the point estimates corresponding to several alternative specifications. The goal is to better characterize the results and evaluate their robustness across alternative samples and specifications. As in Table 7.3, we report the average effects in the lowest two ($<45^{\circ}\text{F}$ and $45\text{--}50^{\circ}\text{F}$) and highest two ($80\text{--}85^{\circ}\text{F}$ and $>85^{\circ}\text{F}$) temperature-day exposure bins, although all models include the ten bins described earlier. These coefficients are shown in columns 1 and 2. Similarly, in columns 3 and 4 we report the average effect of precipitation in the lowest two and highest two precipitation bins. In order to ease comparisons, row 1 shows the baseline estimates including state*year effects that were reported in Table 7.3.

Row 2 reports estimates from a model where state*year effects are replaced by national year effects (i.e. the year effects are restricted to be constant across all counties in the sample). The advantage of this approach is that more residual variation is available for identifying the effects of weather shocks on farm profits. This is generally reflected by smaller standard errors in row 2 versus row 1. The main disadvantage is that the aggregate year effects specification implicitly assumes that input and output prices do not vary within the USA, whereas the state*year effect approach allows prices to vary across states. If the assumption of national prices is invalid, part of the profit response observed reflects price effects and this may confound the predicted long-term impact of climate change on agricultural productivity. Nevertheless, the coefficients in row 2 are all within standard errors of the coefficients in row 1.

Rows 3 and 4 take an intermediate approach by replacing the state*year effects with USDA Farm region and US Census division*year effects. This approach still allows for some geographical variation in farm product prices while preserving more residual weather variation than the state*year model. The results from these two models are within sampling variation of the baseline estimates in row 1. We also conducted F -tests to compare the models in rows 1, 3 and 4 against the model in row 2, which restricts the year effects to be the same across all counties. These three tests generate p -values of less than 0.001, and so the null hypothesis that the year effects are equal across all counties is easily rejected in this sample. It is apparent that there are important local shocks and that it is invalid to assume otherwise.

Row 5 re-estimates the model in equation (7.1) on an unbalanced panel, namely using all valid county observations that appear in any year of the US Census of Agriculture. This results in a larger number of observations (13 533) compared to the 11° 280 in the balanced sample. However, the estimated effects of extreme weather on farm profits in this smaller sample are very similar to the balanced case. Rows 6 and 7 correspond to models estimated separately on counties east and west of longitude 100 ($N = 8670$ and $N = 2610$, respectively). This approach follows from the work of Schlenker et al. (2005, 2006), who argued that pooling across irrigated and

Table 7.4 *Alternative estimates of the effect of growing-season weather on farm profits per acre*

	Average effect of temperature-days		Average effect of total precipitation	
	Less than 45 °F (1)	More than 80 °F (2)	Less than 10" (3)	More than 25" (4)
1. Baseline model (with state*year effects)	-0.0200 (0.0137)	-0.0014 (0.0319)	0.1057 (0.3611)	-0.0188 (0.4546)
2. With year effects	-0.0065 (0.0119)	-0.0257 (0.0264)	0.8894 (0.3197)	-1.5572 (0.5000)
3. With USDA region*year effects	-0.0049 (0.0126)	0.0019 (0.0269)	-0.3261 (0.2995)	-0.8430 (0.5054)
4. With US Census division*year effects	0.0066 (0.0117)	0.0145 (0.0295)	0.0813 (0.3633)	-0.3057 (0.4674)
5. Unbalanced panel	-0.0211 (0.0126)	-0.0072 (0.0285)	0.1318 (0.3101)	0.1625 (0.4432)
6. Counties east of 100th meridian	-0.0192 (0.0162)	-0.0259 (0.0323)	0.0103 (0.0129)	0.1329 (0.6403)
7. Counties west of 100th meridian	-0.0278 (0.0235)	0.0109 (0.0287)	-0.3380 (1.8150)	0.0037 (0.0670)
8. Early growing season (April–June)	-0.0938 (0.0365)	-0.0107 (0.0209)	-0.9494 (1.3108)	-0.0248 (0.0171)
9. Late growing season (July–September)	0.0018 (0.0013)	0.0070 (0.0594)	2.4538 (1.3895)	0.0359 (0.0426)

Notes: All dollar figures in 2005 constant dollars. Unless noted otherwise, all parameter estimates are from fixed effects models where the dependent variable is farm profit per acre; includes soil characteristics, county fixed effects, and state*year fixed effects. Models in row 1, 2, 3, 4, 8 and 9 are based on a balanced sample of 2256 counties for a total of 11 280 county-year observations. Models in rows 5, 6 and 7 are based on sample sizes of 13 533, 8670 and 2610, respectively. Standard errors are clustered by county. See the text for more details.

non-irrigated agriculture has confounded the estimates of the Ricardian models for land values. Deschenes and Greenstone (2007) also implemented a similar analysis for farm profits data by estimating separate effects for counties where 10 per cent or more of farmland is irrigated. While there are some differences in the estimates along the east/west divide, these differences appear small in light of the statistical precision of the estimates. Nevertheless, we note that the effect of low growing-season temperatures is similar in magnitude, while the effect of days above 80 °F of mean temperature is larger in eastern counties. The results also indicate that the very low growing-season rainfall is more detrimental in western counties while the effect of very high rainfall is larger in eastern counties.

Finally, rows 8 and 9 estimate separate effects for early (April–June) and late (July–September) weather on farm profits. This allows for the possibility of differential effects of extreme weather on farm productivity depending on the timing of the shock. For example, rainfall during the early season may be more beneficial than during the late season. The models reported before did not allow for this possibility. The main finding in these rows is that cold days (<45 °F) during the early season are especially detrimental to farm profits. Each day less than 45 °F in the early season significantly lowers profits per acre by \$0.09.

Although not reported in Table 7.4, we also have estimated additional models including separate variables for 11 daily minimum (ranging from <25 to >70, and every 5 °F wide bin in between) and maximum (ranging from <55 to >100, and every 5 °F wide bin in between) temperatures. This analysis suggests that both minimum and maximum temperatures are significant predictors of farm profits per acre. In particular, low daily maximum temperatures are associated with a \$0.05 reduction in farm profits per acre per temperature-day. Finally, we also estimated a variant of the baseline model (row 1), where 12 daily mean temperature bins are included, and where the upper two bins are 85–90 °F and >90 °F. There are relatively few growing-season temperature-days above 90 °F (the farmland weighted average in the sample is 0.25 days per season), so the results must be interpreted with more caution. Nevertheless, the estimated results are similar to the baseline estimates based on 11 growing-season temperature-day bins.

There are three key results to be taken from Tables 7.3 and 7.4. First, models for farm profits that specify the effect of growing-season temperature through a series of temperature-day bins fit the data better than models that are based on quadratics in growing-season degree-days. Second, the data support models allowing for year effects that vary geographically, either at the state or regional level, and so it is apparent that there are important local price shocks that affect farm profits. Finally, it is also evident that the alterations to the baseline specification we considered, including separate effects within the growing season, separate effects for daily minimum and maximum temperature and separate effects across the 100th meridian, fail to lead to a meaningful change in the estimates of the effect of extreme temperatures on farm productivity.

Table 7.5 further probes the extent of geographical difference in the response function linking farm productivity and temperature extremes by reporting estimates specific to each of the nine US Census divisions. These are obtained by fitting separate models for equation (2.3) separately by US Census divisions. The point estimates reported in the

Table 7.5 Estimates of the effect of growing-season weather on farm profits per acre by US Census division

	Average effect of temperature-days:		Observations (3)
	Less than 45°F (1)	More than 80°F (2)	
Census division			
1. New England	0.1723 (0.6243)	0.0329 (0.1489)	260
2. Middle Atlantic	0.1962 (0.1318)	0.0105 (0.0543)	610
3. East North Central	-0.0540 (0.0624)	-0.0127 (0.0238)	1480
4. West North Central	0.0329 (0.0263)	-0.0572 (0.0199)	2125
5. South Atlantic	-0.0745 (0.0491)	-0.3640 (0.2520)	1845
6. East South Central	-0.0135 (0.0549)	0.0520 (0.1281)	1175
7. West South Central	-0.0032 (0.0101)	0.0933 (0.0806)	1960
8. Mountain	-0.0475 (0.0289)	-0.0308 (0.0270)	240
9. Pacific	-0.0500 (0.0541)	0.1124 (0.0592)	625
10. Farmland weighted sum of division-specific estimates	-0.0127 (0.0522)	0.0028 (0.0565)	
11. Baseline estimate (from Table 7.3)	-0.0200 (0.0137)	-0.0014 (0.0314)	

Notes: All dollar figures in 2005 constant dollars. All parameter estimates are from fixed effects models where the dependent variable is farm profit per acre; includes soil characteristics, county fixed effects, and state*year fixed effects. Standard errors are clustered by county. See the text for more details.

table are obtained in a similar fashion as the baseline estimates in row 1 of Table 7.4 (i.e. reporting the average of the lowest and highest two temperature bin coefficients). In addition, column 3 in Table 7.5 reports the number of county*year observation in each Census division.

The main point that emerges from Table 7.5 is that there is substantial heterogeneity in the estimated effects of extreme temperatures on farm productivity. For example, the impact of temperature-days above 80°F on profits per acre ranges from -0.36 to 0.11. Notably, the estimated effect of high temperature-days is negative in four out of nine divisions, and statistically significant in only one out of nine divisions (West North Central). The estimated impacts of temperature-days below 45°F are also mixed and generally statistically imprecise, with negative effects in six out of nine divisions, none of which is statistically significant at the 5 per cent level.

The last two rows to Table 7.5 report aggregate (i.e. national) estimates. Row 10

aggregates the division-specific estimate by taking a weighted sum where the weights correspond to the share of total farmland in each division. Row 11 reproduces the baseline estimates from Table 7.4. It is evident that the national estimates derived from the division-specific ones are largely similar in magnitude to the ones from the pooled model that restricts the effect of temperature (and of all the other model variables) to be the same across all counties. Consequently, we proceed with a model that restricts the growing-season weather effects to be same across all counties.

Projected Impacts of Climate Change on US Agricultural Sector Profits

Optimal decisions about climate change policies require estimates of individuals' willingness to pay to avoid climate change over the long run. This section assesses the magnitude of the estimated impacts for the agricultural sector in the USA and discusses some caveats to this exercise.

Table 7.6 presents the present discounted value (PDV) of the expected change in aggregate agricultural profits associated with predicted changes in climate during the twenty-first century according to the CCSM3 A2 model. The calculations based on equation (7.4) are for the specification that models growing-season temperature using 11 bins in daily average temperature. We use a discount rate of 3 per cent and report the estimates for four horizons: 2010–39, 2040–69, 2070–99 and 2010–99. Standard errors are reported in parentheses below each estimated impact.

The columns in Table 7.6 correspond to four specifications of the year effects in the farm profits models: (1a) national year effects (i.e. restricted to be the same across all counties); (1b) USDA region-specific year effects; (1c) US Census division-specific year effects; and (1d) state-specific year effects. As discussed earlier, these four specifications allow for a varying degree of geographical variation in input and output prices. Panel A is based on models for all counties in the sample. Panel B restricts the analysis to counties east of the 100th meridian, as in Schlenker et al. (2006).

Across the specifications in columns 1a to 1d of Panel A, the 2010–99 PDVs range from –\$182 billion to +\$15 billion, and would be judged to be statistically significant in one of the four specifications. Weighted by the inverse standard errors across the four columns in Panel A of Table 7.6, the summary measure is a PDV of –\$28 billion. The same calculation for the counties east of the 100th meridian generates a summary PDV of –\$63.1 billion.

To put these estimates in some context, we note that the historical annual average profits in the US agricultural sector are about \$38.7 billion (for the counties included in the sample). Thus, under the unrealistic assumption that there will not be any technological improvement or adaptation in response to the higher temperatures over the next 90 years, the estimates imply that climate change will cause a loss roughly equivalent to 0.7–1.6 years of typical profits in the agricultural sector. Of course, the loss would be larger with a smaller discount rate and smaller with a larger discount rate.

There are a number of caveats to these calculations, and to the analysis more generally, that bear noting. First, the effort to project outcomes at the end of the century requires a number of strong assumptions, including that the climate change predictions are correct, relative prices will remain constant, the same technologies will prevail and

Table 7.6 Estimates of the present discounted value of the predicted climate change impacts on total agricultural profits, by 30-year periods

	(1a)	(1b)	(1c)	(1d)
<i>PDV of predicted annual impact over 2010–99</i>				
A. All counties in sample	–181.8 (89.5)	–48.9 (130.2)	15.3 (116.0)	–57.9 (160.2)
2010–39	–72.0 (45.9)	–16.9 (66.8)	22.1 (58.4)	–27.8 (81.3)
2040–69	–62.0 (25.2)	–17.2 (36.6)	–2.2 (33.2)	–18.6 (45.5)
2070–99	–42.8 (16.2)	–12.7 (23.5)	–4.0 (21.6)	–10.3 (29.4)
<i>PDV of predicted annual impact over 2010–99</i>				
B. Counties east of 100th meridian	–212.6 (54.8)	–131.1 (71.8)	–103.4 (65.0)	–10.3 (76.6)
Year effects	Yes	No	No	No
USDA region*year effects	No	Yes	No	No
Census division*year effects	No	No	Yes	No
State*year effects	No	No	No	Yes

Notes: PDV calculations use a 3% discount rate, and figures are in billions of 2005 constant dollars. Each county's predicted impact is calculated as the discrete difference in per acre profits at the county's predicted degree-days and precipitation (or predicted distribution of temperature-day bins and precipitation) after climate change and its current climate (i.e. the average over the 1970–2000 period). The resulting change in per acre profits is multiplied by the number of acres of farmland in the county and then the national effect is obtained by summing across all 2256 counties in the sample. Average annual aggregate profits in the 2256 counties in the sample are 38.7 billion (\$2005). Standard errors are clustered by county and assume independence of the predicted impacts across years. See the text for more details.

that the farming practices and the geographic distribution of farmland will remain unchanged. These assumptions are strong and pessimistic, but their benefit is that they allow for a transparent analysis that is based on the available data rather than on unverifiable assumptions.

First, some models of climate change predict increases in extreme events (e.g. droughts and floods) or the variance of climate realizations, in addition to any effects on growing-season temperature and precipitation distribution. Our analysis is uninformative about the economic impact of these events. If the predictions about these events are correct, a full accounting of the welfare effects of climate change would have to add the impacts of these changes to the impacts presented here. Similarly, it is thought that permanent changes in climate will disrupt local ecosystems and/or change soil quality. Both of these factors may affect agricultural productivity. Since annual fluctuations in climate are unlikely to have the same effect on ecosystems and soil quality as permanent changes, our estimates fail to account for these effects as well.

Second, as its name suggests, global climate change will affect agricultural production around the globe. It may be reasonable to assume that this will alter the long-run costs of production, and this would cause changes in relative prices. Since our estimates are based on annual fluctuations in weather and are adjusted for state*year fixed effects, it is

unlikely that they fully account for this possibility. It is noteworthy that other methods used to infer the welfare costs of climate change such as the hedonic approach are also unable to account for such changes, because the land value–climate gradient is estimated over the existing set of prices.

Third, there is a complex system of government programs that impact agricultural profits and land values by affecting farmers' decisions about which crops to plant, the amount of land to use and the level of production (Kirwan, 2009). Our estimates would probably differ if they were estimated with an alternative set of subsidy policies in force. This caveat applies to all other methods that infer the cost of climate change using historical data, including the hedonic method.

Fourth, our measure of agricultural profits differs from an ideal case in some important respects. In particular, interest payments are the only measure of the rental cost of capital in the Censuses. Thus our measure understates the cost of capital by not accounting for the opportunity cost of the portion of the capital stock that is not leveraged. Furthermore, our measure of agricultural profits does not account for labor costs that are not compensated with wages (e.g. the labor provided by the farm owner).

Finally, we discuss two caveats that would lead to an overstatement of the damage associated with climate change. First, as we have emphasized, our approach does not allow for the full set of adaptations available to farmers. In this case, the direction of the bias can be signed because farmers will only undertake these adaptations if the benefits exceed the costs. Second, elevated carbon dioxide (CO₂) concentrations are known to increase the yield per planted acre for many plants (see, e.g., Miglietta et al., 1998). Since higher CO₂ concentrations are thought to be a primary cause of climate change, it may be reasonable to assume that climate change will lead to higher yields per acre. The approach proposed in this chapter does not account for this 'fertilizing' effect of increased CO₂ concentrations.

CONCLUSION

In recent years there have been many studies of the potential impacts of climate change on the US agricultural sector. These have been based on three distinct broad methodologies: integrated assessment models/simulations; Ricardian analysis of farmland values and climate, and fixed effects analysis of the effect of year-to-year fluctuations in weather on farm productivity.

This chapter has presented a new application of the later method by implementing the model on data from the 1987–2007 Census of Agriculture. Importantly, the methods presented in this chapter incorporate and confirm an emerging literature's finding that the most important impacts of temperature are at the extremes, and flexible functional forms are necessary to capture these nonlinearities. The empirical results also highlight the importance of controlling for local price and productivity shocks.

Using climate change predictions from the CCSM3 A2 model, the PDV over the remainder of the century of the projected impacts is roughly \$28 billion, or 0.7 year of current annual profits. This estimate is likely to overestimate the loss because it fails to allow for any technological advances or adaptation in response to higher temperatures.

Based on this, we believe that the case for large negative impacts of climate change on aggregate profits in the US agricultural sector is limited. In contrast, recent research suggests that there may be substantial negative impacts on agriculture and health in poorer countries, especially those with already intemperate climates (Guiteras, 2009; Burgess et al., 2011). However, the general area of the likely economic impacts of climate change remains immature and much further research is necessary.

NOTES

1. See e.g., Adams et al. (1990), Deschenes and Greenstone (2007), Guiteras (2009), Dinar et al. (1998), Kelly et al. (2005), Mendelsohn et al. (1994), Schlenker et al. (2005, 2006), Schlenker and Roberts (2009).
2. Similar methods have been used to infer the impact of climate change on human health. See Deschenes and Greenstone (2011), Deschenes et al. (2009), Barecca (2010).
3. We also present results where the state*year effects are replaced by national year effects, USDA region-specific year effects, and US Census division-specific year effects.
4. The panel data method proposed by Deschenes and Greenstone (2007) has been applied in many papers since, including Guiteras (2009), Costello et al. (2008), Schlenker and Roberts (2009), Welch et al. (2010). In addition, the method has been applied to studies of the likely human health impacts of climate change (Barreca, 20, Deschenes and Greenstone, 2008 and Deschenes et al. 2009), and the impact of climate change on electricity demand (Aroonruengsawat and Auffhammer, 2010).
5. An exception is that it includes receipts from placing commodities in the Commodity Credit Corporation (CCC) loan program. These receipts differ from other federal payments because farmers receive them in exchange for products.
6. For example, the 2002 technical documentation reports that 'the value of crops sold in 2002 does not necessarily represent the sales from crops harvested in 2002. Data may include sales from crops produced in earlier years and may exclude some crops produced in 2002 but held in storage and not sold'.
7. In a recent article, Welch et al. (2010) find that rice yields in Asia are reduced by increases in daily minimum temperature while increases in daily maximum temperature increase yields.
8. Schlenker et al. (2010) discovered and documented errors in the weather data used in Deschenes and Greenstone (2007). The samples used in this chapter are not affected by these errors.
9. Other selection rules did not lead to noteworthy differences in the derived weather data.
10. The degree-days variable is calculated so that a day with a mean temperature below 46°F contributes 0 degree-days; between 46°F and 90°F it contributes the number of degrees F above 46 degree-days; above 90°F it contributes 44 degree-days.
11. To the best of our knowledge, the daily-level model data from CCSM3 A2 do not contain sufficient model-based predictions to construct the historical baseline directly from the GCM. An alternative would be to derive climate change predictions using monthly-level model data, which are typically available for a longer time span (i.e. 1950–2099) and allow for correction of any model error by comparing the model-predicted historical baseline with the actual historical baseline. A limitation is that it is necessary to make assumptions about the within-month distribution of daily temperatures. Specifically with monthly-level model data, it is necessary to assume that monthly minimum and maximum temperatures apply equally to all days within a month or to make some other assumption that permits inference on a daily-level variable from a monthly-level variable. There are pluses and minuses to both approach and it is not obvious, at least to us, that either is superior.
12. Information on farm production expenses is only available starting in the 1987 Census of Agriculture.
13. Average profits per acre are weighted by the total farmland in a county-year.
14. See <http://www.ers.usda.gov/briefing/arms/resourcereions/resourcereions.htm>.
15. Averages are weighted by the fraction of growing-season days in each temperature and precipitation category.

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8 The impact of climate change on US agriculture: a repeated cross-sectional Ricardian analysis

Emanuele Massetti and Robert Mendelsohn

INTRODUCTION

Controlled laboratory and field experiments suggest a hill-shaped relationship between yield and temperature (see Reilly et al., 1996, Mendelsohn and Dinar, 2009). For each crop there is an ideal temperature and precipitation range. Climate that is either warmer or cooler than this optimal range leads to lower yields. Across crops there is a similar relationship that involves both yields and the profitability of each crop. It follows that one should expect a hill-shaped relationship between temperature and gross revenues as well. However, farmers can choose outputs to adapt to different temperatures. They can switch crops, switch livestock, and/or move from crops to livestock. They can also change inputs in response to temperature such as adjusting fertilizer, irrigation and pesticides. Finally, they can adjust management by altering planting and harvest dates or tilling practices as a climate adaptation. All of these choices lead to a less concave net revenue–temperature function than the pure yield–temperature relationship would suggest. By altering inputs, outputs and management, farmers can make their choice set less concave by moving to more advantageous combinations of outputs as well as inputs. A less concave response function implies lower sensitivity to climate change. Agro-economic models consequently overestimate the welfare impact of climate change because they focus on the relationship between climate and yields, holding farmer choices constant. They neglect the possibility that farmers will react to a changing environment by altering their behavior. They mis-estimate the general relationship between net revenue and climate, and predict a function that is far more concave than the one that will probably take place.

Another approach estimates the relationship between net revenue and weather using intertemporal variations (Deschenes and Greenstone, 2007). This intertemporal approach captures the myriad of individual yield functions used by each farmer, so this is a good aggregation device. As with the controlled experiments, this technique does not capture adaptation because farmers cannot anticipate weather and therefore cannot adjust to it. The intertemporal approach provides a solid measure of the influence of weather but a poor measure of the impacts of long-term climate change because it does not capture adaptation.

More sophisticated agro-economic approaches have explicitly introduced adaptation possibilities in terms of crop and livestock and inputs switching (Adams et al., 1990, 1999). These optimization models have shown that at least US farmers will benefit from moderate climate change (Adams et al., 1999, Alig et al., 1997). The ideal framework would extend this research to the entire world. The ideal model would also need to extend the analysis to capture changes in inputs and farming practices. Such a global

long-term model of land use could then capture the evolution of land prices, crop and livestock prices, input prices, technology and other major variables that influence farmers' activities. However, this is an ambitious project that still is far from complete. There remain vast parts of the world where very little is known about agriculture and a thorough detailed model has yet to be done even in the USA, the epicenter of such modeling.

Another way to capture adaptation is to apply a cross-sectional analysis across climate zones. For example, yield–climate response functions can be estimated for a specific crop across climate zones (Gbetibouo and Hassan, 2005, Schlenker et al., 2006). By comparing farm yields across climate zones, one can see what happens to the yields of a specific crop as farmers adjust their inputs and management practices. The results tend to show that there is still a concave relationship between yield and temperature, but the response function is much less concave than the controlled experiments suggest.

In order to capture endogenous output choice, another strategy is to use the Ricardian method, which estimates the relationship between land value and climate (Mendelsohn et al., 1994). This method estimates the outer envelope of land values or net revenues from each output choice. It effectively captures the optimal combination or envelope of all possible yield–climate functions. With competitive markets, land values reflect the long-term profitability of each of these alternative farm activities. They measure the expected future flow of net revenue from agriculture, including expectations of alternative possible land uses outside of agriculture. If they are estimated using a cross-section across different climate zones, they reflect long-term adaptations to climate. Land values in a competitive land market will reflect the long-term productivity of land as first observed by David Ricardo.

The Ricardian method (Mendelsohn et al., 1994) has been applied successfully in over 27 countries across the world (Mendelsohn and Dinar, 2009). The results reveal that moderate climate change is beneficial for temperate and polar regions while it is harmful for low-latitude countries. The inclusion of all forms of farmer adaptation leads to predictions of much less harmful damages.

However, the Ricardian method does not explicitly measure adaptation. It does not identify how farmers adapt; it merely measures the resulting consequences of adaptation. In order to provide evidence of how farmers adapt, a new set of studies has begun to model adaptation explicitly. These studies confirm the intuition that adaptation by farmers is possible by illustrating the current methods of adaptation in different climate zones. For example, the studies reveal that farmers around the world already adjust which crops to plant (Kurukulasuriya and Mendelsohn, 2008; Seo and Mendelsohn, 2008a; Wang et al., 2009) and which livestock to raise (Seo and Mendelsohn, 2008b) to optimize net revenues in their current climate.

The Ricardian method has been criticized for being too optimistic that farmers will adapt to climate change. Kelly et al. (2005) argue that the Ricardian method estimates a lower bound on climate change impacts because it assumes full adaptation. The Ricardian method is a comparative static analysis between two long-term equilibria and does not address the transition costs between them. Intertemporal evidence on adoption of new technologies supports this claim, as farmers can be slow to embrace innovations (Reilly, 1995). However, the rapid annual output changes in response to price changes suggest that farm adaptation can also be very quick. In agriculture the capital tied to

a single crop is relatively easy to change, with the major exception of large infrastructure water projects. If climate changes slowly over the century, farmers will have many opportunities to adjust their on-farm capital to reflect changing conditions. The decadal adjustment costs should be low. Most importantly, the majority of adaptation measures will be autonomous, without the need for state intervention to plan and finance response actions. In contrast, adjusting large water projects to reflect climate change could indeed involve high transition costs, causing regions that are dependent on irrigation possibly to incur higher costs than the Ricardian method suggests.

Another methodological critique of the Ricardian model concerns whether the estimated results are robust (Deschenes and Greenstone, 2007) (DG). DG estimate repeated cross-sections of the Ricardian model in the USA across several agricultural Census years (1978, 1982, 1987, 1992, 1997 and 2002). They show that the Ricardian response function is not stable. The impacts of climate change on US agriculture vary greatly over this period, showing a trend from positive to negative impacts. These repeated cross-sections cast doubt about the reliability of the Ricardian method. DG argue that the estimates of the coefficients are inherently biased due to unobserved characteristics that are correlated with climate variables, and present a time trend not controlled by the Ricardian method.

This chapter examines the repeated cross-sections estimated by DG. The purpose of this chapter is to examine whether there are modifications to the DG model that can make the cross-sectional Ricardian method more robust. The analysis corrects a number of limitations of the model estimated by DG.

We start by estimating the Ricardian model for all six Census years using the repeated cross-section method of DG. We employ the same functional form and the same set of variables and counties. Next, we introduce an improved measure of climate that corrects for errors in their measurement of climate (Fisher et al., 2011). Not only does this provide a more accurate measure of climate, it also expands the coverage of the sample from 72 per cent to 97 per cent of total agricultural land in the USA (Figure 8.1 – see p. 249). While the Ricardian literature began using a linear model, the distribution of land values in the USA is log-linear. We therefore introduce a log-linear Ricardian model. Finally, we introduce a larger set of covariates to control for non-climate determinants of land values. Of course, including more explanatory variables does not guarantee that all possible explanatory variables have been included. The possibility that omitted variables continue to influence the results is a shared weakness of all empirical studies that rely on uncontrolled experiments. Confidence intervals are provided for all estimates. We correct standard errors for the spatial correlation of residuals.

For all of these Ricardian models, the impact of climate change is estimated using three different climate scenarios by 2100: a uniform benchmark scenario and two climate model scenarios.

The rest of the chapter is organized as follows. We first introduce the standard Ricardian model. We then describe the data set used in the analysis. Next, we examine the different empirical results from using more complete data, a log-linear functional form and more explanatory variables. The next section describes three climate scenarios for 2100. Combining the estimated regression coefficients with these climate projections, we present the estimates of climate impacts for each model. We conclude with a review of the main results and a discussion of their implications.

THE RICARDIAN MODEL

Following Mendelsohn et al. (1994), we assume that each farmer maximizes income subject to the exogenous conditions of their farm. Specifically, the farmer chooses the inputs and the combination of crop and/or livestock (indexed by j) that maximizes net revenue for each unit of land:

$$\text{Max}\pi_i = \sum_{j \in J} P_{ij} Q_{ij}(X_{ij} | C_i, W_i, S_i) - \sum_{j \in J} P_{ij} X_{ij} \quad (8.1)$$

where π_i is the net revenue of farm i , P_{ij} is a vector of input and output prices Q_{ij} is the production function for each crop or livestock j , X_{ij} is a vector of endogenous input choices such as seeds, fertilizer, irrigation, pesticides, hired labor and capital, C_i is a vector of climate variables, W_i is a vector of economic control variables and S_i is a vector of soil characteristics. Note that j denotes a choice set of outputs that includes any combination of crops and livestock.

Differentiating (8.1) with respect to each input identifies the set of inputs that maximizes net revenue. The resulting locus of net revenues for each set of exogenous variables is the Ricardian function. It describes how net revenue will change as exogenous variables change:

$$\pi^* = \pi(C, W, S | P_{ij}) \quad (8.2)$$

Assuming perfect competition for land, land value will be equal to the present value of the net revenue of each farm:

$$V_{land} = \int_0^{\infty} \pi_i^* e^{-rt} dt \quad (8.3)$$

where r is the market interest rate.

The literature concerning the climate sensitivity of individual crops and livestock suggests a hill-shaped relationship between yield and temperature (see Reilly, 1995, Mendelsohn and Dinar, 2009). The Ricardian literature also predicts a hill-shaped relationship between annual temperature and net revenue (Mendelsohn and Dinar, 2009). With crop and livestock switching, farmers can make their choice set less concave by moving to more advantageous combinations of outputs as well as inputs as climate changes (Mendelsohn et al., 1994). It follows that the more limited the set of choices available to a farmer, the more concave the climate response function. Of course, the concavity of the response function can be quite different depending on the set of choices that a farmer is restricted to.

We estimate two functional forms in this chapter. The linear form looks as follows:

$$V_i = a + b_1 T + b_2 T^2 + b_3 P + b_4 P^2 + mG + \varepsilon_i \quad (8.4)$$

where the dependent variable is land value per hectare of land, T and P represent a vector of seasonal temperature and precipitation variables, G represents a vector of relevant control variables, ε is an error term and the other parameters are coefficients. In this analysis we rely on seasonal temperature and precipitation variables.

A major improvement introduced here is the use of a log-linear model to estimate the Ricardian function. Although Ricardian studies began using a linear relationship between land values and climate, land values are log-normally distributed in the USA. The log-linear form is

$$\ln V_i = a + b_1T + b_2T^2 + b_3P + b_4P^2 + mG + \varepsilon_i \quad (8.5)$$

Estimates of climate coefficients can be used to compute the marginal effect of climate change. With the linear form, the effect of climate is additive. For example, the marginal effect of an increase in temperature evaluated at temperature T is

$$dV/dT = b_1 + 2b_2T \quad (8.6)$$

With the log-linear form, the effect of climate is proportional. For example, the marginal effect of a change in temperature is

$$dV/dT = V(b_1 + 2b_2T) \quad (8.7)$$

With the log-linear functional form, the coefficients determine the percentage change in land value.

In this study, we estimate a separate Ricardian function using cross-sectional data from each Census year between 1978 and 2002. This will lead to six equations for each functional form. In each case, we estimate a weighted least squares regression using the square root of farmland in a county as the weight. One question that has been raised by DG is whether these coefficient estimates are the same over time. We shall examine this by comparing the coefficients directly, comparing the marginal impacts of climate and comparing the predicted impacts of selected climate scenarios.

The welfare impact W of climate change on US agriculture is obtained by computing the difference between the value of farmland under the new climate and the value of farmland under the current climate. We find that DG make a technical error when computing the welfare effects. DG use the following equation for welfare:

$$W_t = \sum_i [V_{i,t}(C_1) - V_{i,t}(C_0)] F_{i,t} \quad (8.8)$$

One reason that welfare changes in each time period in the DG estimation is that they use a different level of farmland in each year. In order to test whether the climate coefficients are stable over time, we use the same level of farmland in every year. In this case, we use the expected value of farmland in each county:

$$W_t = \sum_i [V_{i,t}(C_1) - V_{i,t}(C_0)] E[F_{i,t}] \quad (8.9)$$

Of course, the best forecast of welfare effects in the future should rely on the expected value of future farmland (not past farmland). This would require modeling not only how farmland is expected to change over time from technological and economic forces, but also how it might change in response to climate change (Mendelsohn et al., 1996). In the

present analysis we employ a less sophisticated approach and we use the average number of acres of farmland between 1978 and 2002.

Because the Ricardian model allows farmers to switch across all endogenous choices (crop species, livestock species, irrigation, fertilizer and so on), it fully captures adaptation. Farmers can endogenously adjust all their choices as conditions change. This is a great strength of the Ricardian method. The model also captures long-run adjustments made by the ecosystem. Changes in pests, weeds and insects due to climate are all captured in the analysis. Because the model does capture these long-run adaptations, it is less suitable for modeling short-run changes in weather. Farmers have much less opportunity to adapt to short-run weather fluctuations. Short-run studies of intertemporal weather (Deschenes and Greenstone, 2007) are good measures of acute effects but are less appropriate measures of the long-run impacts of climate change.

The analysis assumes that prices remain unchanged (Cline, 1996). Although changes in local supply might be dramatic, prices of food crops are determined by global markets. With the expansion of crop production in some parts of the world and the contraction in others, the change in the price of crops from global warming is expected to be small if global mean temperature increase will be below 5.5 °C (Easterling et al., 2007). The omission of price effects implies that the Ricardian method will overestimate both damages and benefits. The analysis also does not take into account carbon fertilization from the higher CO₂ concentrations. The omission of CO₂ effects suggests that the estimates will overestimate damages and underestimate benefits.

DATA

Following DG, we have constructed a balanced panel with observations from the contiguous 48 states over the US Agricultural Census years of 1978, 1982, 1987, 1992, 1997 and 2002. Units of measurement follow the metric system; economic variables have all been converted to constant 2000 US dollars using the GDP deflator. Many counties are missing in the DG analysis because of missing climate data. The DG analysis has only 2124 counties of the 3048 counties in the lower 48 states that have agriculture. By replacing missing climate data, we are able to include 2914. Our analysis is based on 97 per cent of US farmland whereas the DG analysis is based on only 72 per cent. It is not clear why DG omit so many counties from their analysis since data are available for most of them.

We rely on the 1971–2000 monthly precipitation and mean temperature normals computed by the National Climatic Data Center for 7467 weather stations in the contiguous 48 states. We assume that climate has not changed over this time period. In practice, there has been a small increase in temperature over this period of 0.5 °C. However, this should not bias the climate coefficients because it has been an almost uniform increase across the 48 states. In contrast, DG create a climate variable that changes by design. They measure climate as the average of the weather from 1970 to the year of each observation. In their analysis the climate for farmers in 1978 is the average of weather between 1970 and 1978, whereas the climate for farmers in 1982 is the average of the weather from 1970 to 1982. The weather between 1978 and 1982 thus changes the measured climate variable even though the actual climate has changed only marginally. This mismeasurement of climate

introduces noise in to their climate variable, biasing the coefficient towards zero and causing the climate coefficients to vary across census years.

Following Mendelsohn et al., we estimate a quadratic climate surface as a function of longitude, latitude, elevation and distance from coastline for the contiguous 48 states. A separate surface is estimated using weather stations within 500 miles for each county. A total of 2914 regressions is therefore estimated for each climate variable. The data are weighted to give nearby stations more weight. The predicted values from that estimated surface for each county are used to yield monthly climate variables for that county. The seasonal climate is the arithmetic average of climate variables in winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). In contrast, DG use just the single months of January, April, July and October to represent the four seasons.

For farmland value, land in farms and other agricultural data, we rely on the US Census of Agriculture (USDA, 1980, 1984, 1989, 1994, 1999, 2004). The dependent variable in our panel is the average estimated value of land and buildings per hectare of land in farm.

We include several explanatory variables not used in DG. We measure the long-term availability of water to farmers using the average fresh surface water used between 1985 and 2000 for each county from the US Geological Survey (Solley et al., 1988, 1993, 1998; Hutson, 2004). This long-run access to surface water can be largely considered as exogenous, depending on long-term surface flows and historical rights for water use rather than on markets (Mendelsohn and Dinar, 2003). Data about greenhouses and government subsidies to farmers by county are included from the Census of Agriculture. We use the median value of owner-occupied housing in each county as a proxy for the opportunity cost of keeping land in farms. These data are available at the county level from the US Census of Population and Housing every ten years. We construct estimates of house values for 1978, 1982, 1987, 1992, 1997 and 2002, extrapolating linear trends from the three Census years of 1980, 1990 and 2000.

The appendix at the end of this chapter contains a more detailed description of the data set and of the variables used in the regressions.

THE RICARDIAN RESULTS

Table 8.1 presents a Ricardian model that is quite similar to the repeated cross-sectional model estimated by DG. The model has a limited number of counties, a limited set of covariates and a linear Ricardian functional form. However, it is not exactly the same as the published DG results because the climate variables have been replaced with reliable estimates (see Fisher et al., 2011). The climate coefficients tend to be significant in all of the regressions. Comparing the climate coefficients across regressions reveals that they are consistent across years. The signs of the climate coefficients are generally the same every year. The squared terms for winter, spring and summer temperature are not significant. The coefficient of the squared term of autumn is positive and significant, implying that autumn temperature has a U-shaped relationship with land value. However, as found by DG, the magnitudes of the climate coefficients vary across years. For example, the coefficient on the linear winter term ranges from -1571 in 1978 to -551 in 1987.

Table 8.1 Basic linear model with limited observations

Model	1978	1982	1987	1992	1997	2002
Temp. winter	-1570.52 (-14.351)	-1058.143 (-10.118)	-551.407 (-7.077)	-635.164 (-6.99)	-915 (-9.418)	-1113.639 (-8.023)
Temp. winter sq.	-44.299 (-7.839)	-15.955 (-2.436)	-11.25 (-2.505)	-9.316 (-1.758)	-22.853 (-4.419)	-23.771 (-3.466)
Temp. spring	1024.617 (3.92)	768.157 (2.873)	533.228 (2.941)	724.566 (3.395)	818.27 (3.552)	820.7 (2.713)
Temp. spring sq.	-36.588 (-2.863)	-33.727 (-2.432)	-29.573 (-3.388)	-42.496 (-3.802)	-40.138 (-3.327)	-40.46 (-2.687)
Temp. summer	-968.104 (-2.167)	-1182.888 (-2.261)	3.118 (0.009)	-566.202 (-1.349)	-229.924 (-0.547)	-337.48 (-0.631)
Temp. summer sq.	-15.86 (-1.753)	-0.054 (-0.005)	-16.205 (-2.373)	-4.773 (-0.561)	-18.428 (-2.108)	-24.754 (-2.2)
Temp. autumn	1177.257 (2.908)	1354.31 (2.74)	254.07 (0.76)	540.438 (1.356)	483.036 (1.178)	1115.847 (2.229)
Temp. autumn sq.	85.06 (4.804)	41.864 (2.075)	48.884 (3.531)	47.516 (2.92)	66.917 (3.675)	63.008 (2.645)
Prec. winter	39.181 (5.421)	32.186 (4.049)	23.742 (4.316)	27.365 (4.355)	33.242 (4.799)	36.36 (3.541)
Prec. winter sq.	-0.042 (-1.279)	-0.061 (-1.55)	-0.069 (-2.685)	-0.054 (-1.72)	-0.036 (-0.999)	-0.02 (-0.317)
Prec. spring	19.206 (1.288)	50.677 (2.96)	22.052 (1.76)	27.059 (1.874)	18.566 (1.309)	32.146 (1.812)
Prec. spring sq.	-0.183 (-2.481)	-0.28 (-3.463)	-0.15 (-2.4)	-0.175 (-2.577)	-0.142 (-1.981)	-0.23 (-2.512)
Prec. summer	3.937 (0.37)	-19.507 (-1.712)	-4.08 (-0.542)	-9.422 (-1.146)	-15.859 (-1.841)	-9.692 (-0.921)
Prec. summer sq.	0.038 (0.593)	0.106 (1.524)	0.002 (0.054)	0.042 (0.863)	0.085 (1.722)	0.039 (0.7)
Prec. autumn	-94.006 (-4.272)	-91.013 (-3.431)	-44.841 (-2.542)	-54.429 (-2.63)	-53.304 (-2.428)	-50.953 (-1.637)
Prec. autumn sq.	0.422 (3.512)	0.465 (3.195)	0.342 (3.495)	0.336 (2.925)	0.289 (2.271)	0.256 (1.289)
Salinity	39.229 (0.113)	338.113 (0.837)	170.604 (0.615)	66.437 (0.223)	12.542 (0.043)	-36.823 (-0.102)
Flooding	-801.662 (-1.814)	-645.322 (-1.737)	-369.086 (-2.131)	-553.695 (-3.319)	-439.754 (-2.243)	-700.902 (-2.736)
Wet index	2575.97 (7.528)	1849.963 (6.091)	217.165 (1.084)	455.559 (2.11)	513.986 (2.121)	165.053 (0.566)
<i>k</i> factor	-7630.109 (-6.179)	-5409.107 (-4.398)	-4276.947 (-4.986)	-4387.225 (-4.624)	-5465.305 (-5.37)	-6061.144 (-4.764)
Length of slope	1.795 (4.918)	2.17 (5.198)	1.234 (4.542)	1.415 (4.275)	1.796 (4.965)	1.576 (3.115)
Sand	-209.1 (-0.482)	-26.58 (-0.06)	-816.792 (-2.557)	-1228.059 (-3.092)	-988.298 (-2.517)	-1399.976 (-2.597)
Clay	-692.375 (-2.51)	-452.629 (-1.53)	-41.06 (-0.181)	-742.212 (-3.187)	-784.042 (-3.377)	-821.475 (-2.578)
Moisture level	14195.161 (5.58)	10392.144 (4.249)	2138.895 (1.392)	-468.886 (-0.27)	1997.238 (1.082)	-286.999 (-0.104)
Permeability	-60.222 (-0.629)	-125.25 (-1.304)	14.852 (0.203)	9.48 (0.107)	4.726 (0.062)	73.764 (0.776)

Table 8.1 (continued)

Model	1978	1982	1987	1992	1997	2002
Income	333.344 (3.84)	251.559 (3.17)	5.846 (0.072)	-71.397 (-0.709)	-10.522 (-0.123)	-82.462 (-0.724)
Income sq.	-0.000006 (-2.2)	-0.000005 (-2.251)	0.000003 (1.082)	0.000004 (1.554)	0.000002 (1.172)	0.000004 (1.454)
Density	16.495 (7.698)	17.439 (7.69)	14.235 (8.875)	16.611 (7.947)	16.184 (7.081)	21.872 (8.255)
Density sq.	-0.006 (-2.537)	-0.008 (-2.655)	-0.006 (-3.34)	-0.007 (-2.727)	-0.01 (-3.205)	-0.012 (-3.641)
Constant	-2364.276 (-0.659)	1029.285 (0.256)	-2393.796 (-0.864)	2397.242 (0.7)	-1556.499 (-0.444)	-1850.879 (-0.411)
Adjusted <i>R</i> -squared	0.689	0.663	0.697	0.656	0.689	0.659

Note: *t*-ratio in parentheses.

Table 8.1 also presents results of the control variables. The control variables have their expected signs. The erosion (*k*) factor and slope length are significant with consistent signs in all Census years. Other significant soil variables include flooding, wetland, sand and soil moisture level. Among the socioeconomic variables, only density and density squared are highly significant in all years. The income variables are significant only in 1978 and 1982. As with the climate coefficients, the coefficients of the control variables are not stable and their magnitude varies over time.

In Table 8.2, we expand the number of counties to cover 97 per cent of total agricultural land in the USA. Specifically, we include a wide number of counties in the center of the USA that were neglected by DG. Many of these counties have very intense agriculture activities. The precipitation coefficients are more significant in Table 8.2 with the wider array of counties. Precipitation in spring appears to be significantly beneficial over all years. The sign of the coefficient of the squared term is also significant and negative, indicating a concave functional form. Summer heat appears to be significantly detrimental for many years. Adding new counties does not change the sign of the climate coefficients, which remain consistent over different years. In addition, the signs and magnitudes of soil and socioeconomic control variables are not affected when the cross-section is enlarged. The lack of stability in the coefficients in Table 8.1 and Table 8.2 implies that there may be some missing variables in the regression.

In Table 8.3 we explore the implications of moving from a linear to a log-linear functional form. The coefficients in Table 8.3 are not the same as in the earlier tables because they now reflect percentage differences rather than absolute differences. In general, the log-linear model fits the data more closely. The errors are more log-normally distributed than normal, making this functional form more appropriate than the linear model.

The number of climate coefficients that are significant increases with the log-linear model although the signs remain the same. The climate coefficients continue to be consistent over time. Higher flooding and *k* factor indices reduce the value of agricultural land. Higher wetland and soil moisture indices are confirmed to be good for agriculture.

Table 8.2 Linear model with more counties

Model	1978	1982	1987	1992	1997	2002
Temp. winter	-1784.831 (-17.468)	-1253.406 (-12.75)	-639.815 (-8.798)	-722.904 (-8.965)	-967.895 (-11.164)	-1108.662 (-9.237)
Temp. winter sq.	-44.68 (-8.442)	-15.537 (-2.513)	-9.276 (-2.295)	-6.158ç (-1.327)	-17.268 (-3.717)	-15.446 (-2.644)
Temp. spring	1062.351 (4.056)	858.861 (3.47)	466.402 (2.589)	577.643 (2.833)	692.597 (3.201)	652.379 (2.324)
Temp. spring sq.	-20.405 (-1.49)	-21.372 (-1.56)	-15.68 (-1.473)	-21.625 (-1.766)	-19.038 (-1.516)	-16.279 (-1.041)
Temp. summer	-1639.175 (-3.462)	-1914.497 (-3.551)	-538.738 (-1.553)	-1163.836 (-2.832)	-877.48 (-2.103)	-1113.826 (-2.236)
Temp. summer sq.	-8.42 (-0.864)	8.851 (0.828)	-6.449 (-0.936)	5.24 (0.633)	-6.976 (-0.819)	-8.379 (-0.823)
Temp. autumn	1937.327 (4.406)	2049.696 (3.967)	801.731 (2.183)	1285.075 (3.068)	1259.432 (2.999)	1930.899 (3.916)
Temp. autumn sq.	58.688 (3.019)	18.297 (0.866)	24.231 (1.505)	12.856 (0.713)	27.598 (1.49)	15.409 (0.679)
Prec. winter	37.55 (5.603)	27.339 (3.749)	24.54 (5.172)	25.99 (4.829)	33.597 (5.582)	35.502 (4.019)
Prec. winter sq.	-0.042 (-1.299)	-0.055 (-1.418)	-0.074 (-3.108)	-0.058 (-2.021)	-0.053 (-1.628)	-0.039 (-0.709)
Prec. spring	27.347 (2.147)	62.419 (4.11)	31.137 (2.83)	40.037 (3.291)	36.391 (2.862)	54.599 (3.535)
Prec. spring sq.	-0.21 (-3.365)	-0.313 (-4.529)	-0.196 (-3.684)	-0.232 (-4.1)	-0.217 (-3.477)	-0.321 (-4.189)
Prec. summer	-8.007 (-0.678)	-34.084 (-2.864)	-14.678 (-1.636)	-21.877 (-2.23)	-25.29 (-2.536)	-23.086 (-1.901)
Prec. summer sq.	0.129 (1.776)	0.205 (2.807)	0.08 (1.432)	0.129 (2.15)	0.154 (2.613)	0.139 (2.039)
Prec. autumn	-108.083 (-5.098)	-106.474 (-4.104)	-60.663 (-3.554)	-71.628 (-3.63)	-74.86 (-3.624)	-77.479 (-2.734)
Prec. autumn sq.	0.463 (3.961)	0.513 (3.61)	0.411 (4.33)	0.413 (3.758)	0.392 (3.313)	0.398 (2.21)
salinity	-116.365 (-0.374)	40.448 (0.118)	-139.808 (-0.638)	-208.598 (-0.881)	-116.624 (-0.461)	-127.9 (-0.42)
Flooding	-971.131 (-1.965)	-754.548 (-1.926)	-461.56 (-2.614)	-565.182 (-3.357)	-585.702 (-2.872)	-692.007 (-3.398)
Wet index	2705.605 (9.106)	1903.222 (7.377)	299.343 (1.827)	505.42 (2.847)	632.976 (3.095)	252.512 (1.08)
k factor	-6928.773 (-5.707)	-4463.743 (-4.071)	-3051.612 (-4)	-3353.053 (-4.183)	-4892.482 (-5.796)	-5284.666 (-4.976)
Length of slope	1.146 (3.28)	1.266 (3.43)	0.781 (2.838)	0.888 (2.867)	1.318 (3.975)	1.278 (3.033)
Sand	-191.155 (-0.5)	8.386 (0.024)	-640.249 (-2.299)	-1208.261 (-3.971)	-911.46 (-2.629)	-1180.509 (-2.328)
Clay	-4.956 (-0.02)	136.602 (0.54)	205.665 (0.998)	-278.345 (-1.324)	-415.264 (-1.801)	-663.988 (-2.086)
Moisture level	15900.718 (5.853)	10826.38 (4.537)	2201.916 (1.577)	300.306 (0.201)	3299.273 (2.002)	746.687 (0.328)
Permeability	30.491 (0.364)	-40.754 (-0.553)	47.348 (0.75)	88.901 (1.38)	47.737 (0.677)	66.134 (0.621)

Table 8.2 (continued)

Model	1978	1982	1987	1992	1997	2002
Income	288.967 (3.214)	250.134 (3.568)	-13.288 (-0.192)	-50.342 (-0.707)	-23.877 (-0.319)	-85.247 (-0.858)
Income sq.	-0.00000418 (-1.438)	-0.00000531 (-2.516)	0.00000289 (1.404)	0.00000315 (1.673)	0.00000256 (1.39)	0.00000366 (1.608)
Density	17.227 (8.368)	18.559 (8.383)	15.443 (9.826)	18.192 (9.108)	17.256 (7.889)	23.39 (9.309)
Density sq.	-0.006 (-2.783)	-0.009 (-2.899)	-0.007 (-3.589)	-0.008 (-3.076)	-0.011 (-3.42)	-0.013 (-3.946)
Constant	1747.236 (0.45)	6062.906 (1.436)	1296.356 (0.471)	5961.336 (1.809)	2536.321 (0.733)	3294.002 (0.784)
Adjusted <i>R</i> -squared	0.705	0.673	0.692	0.649	0.69	0.666

Note: *t*-ratio in parentheses.

The coefficients of income per capita and income per capita squared are significant. The relationship between personal income per capita and land values is found to be concave. Income per capita higher than US\$45 000 reduces land values; however, there is only a handful of counties beyond that threshold.

As a final step we improve the log-linear model by introducing additional control variables. The estimated set of coefficients is displayed in Table 8.4. We include two geographic variables: latitude and elevation. Latitude appears not to significantly affect the level of land values. The coefficient associated with elevation is significantly negative: increasing the elevation of 100 m reduces the value of land by 4 to 5 per cent. We also introduce distance from major metropolitan areas, surface water withdrawals, the share of farm revenue from greenhouses, subsidies from the government and residential property values. The aim of this enhanced set of covariates is to capture omitted variables that may have plagued earlier studies. The coefficients of these new variables are highly significant and they have their expected signs, implying that they belong in the regression. Proximity to major metropolitan areas, high government subsidies, a high opportunity cost of land, greenhouses and surface water withdrawals are associated with higher-valued agricultural land. The enhanced log-linear model also performs better in terms of the adjusted *R*-squared of the regression.

Another way to compare the results in Tables 8.2, 8.3 and 8.4 is to compare the ratio of the predicted value to the actual value in each decile (Buntin and Zaslavsky, 2004). Table 8.5 reveals that the log-linear model has a more uniform predictive power across different deciles of the distribution compared to the linear model. In particular, the predicted means of the first six deciles are very close to the actual means. While the log-linear model tends to underestimate land values for the top deciles of the distribution, the linear model tends to overestimate land values at the lower end of the distribution. The log-linear model however tends to slightly underestimate the actual means. This shortcoming is resolved by introducing a more complete set of covariates (advanced log-linear). The advanced log-linear model does a good job of predicting the actual values over the whole distribution while predicting the sample mean at the same time.

Table 8.3 Log-linear model with more counties

Model	1978	1982	1987	1992	1997	2002
Temp. winter	-0.415 (-14.8)	-0.363 (-13.2)	-0.341 (-12.4)	-0.381 (-13.4)	-0.374 (-13.2)	-0.398 (-13.6)
Temp. winter sq.	-0.00258 (-1.7)	-0.0000663 (-0.0403)	-0.00115 (-0.753)	-0.000968 (-0.61)	-0.00156 (-0.91)	-0.00131 (-0.739)
Temp. spring	0.375 (4.12)	0.319 (3.85)	0.198 (2.29)	0.252 (2.71)	0.262 (3.08)	0.256 (2.83)
Temp. spring sq.	-0.00854 (-1.74)	-0.00782 (-1.9)	-0.00333 (-0.68)	-0.00614 (-1.12)	-0.00466 (-1.15)	-0.00294 (-0.615)
Temp. summer	-1.01 (-6.77)	-0.999 (-6.33)	-0.787 (-5.11)	-1.01 (-6.2)	-0.899 (-5.48)	-0.978 (-5.98)
Temp. summer sq.	0.0121 (3.91)	0.013 (4.03)	0.0084 (2.63)	0.0124 (3.63)	0.00982 (2.98)	0.00988 (2.93)
Temp. autumn	0.732 (4.97)	0.737 (5.22)	0.715 (4.7)	0.843 (5.19)	0.775 (5.68)	0.897 (6.14)
Temp. autumn sq.	0.000383 (0.0551)	-0.00267 (-0.425)	-0.00236 (-0.326)	-0.0037 (-0.473)	-0.00333 (-0.556)	-0.0062 (-0.906)
Prec. winter	0.0122 (6.68)	0.0107 (5.67)	0.0138 (7.99)	0.0148 (7.83)	0.0155 (8.69)	0.0145 (7.71)
Prec. winter sq.	-0.0000387 (-4.47)	-0.0000363 (-3.98)	-0.0000478 (-5.97)	-0.0000479 (-5.57)	-0.0000548 (-7.13)	-0.0000537 (-6.63)
Prec. spring	0.0261 (6.07)	0.033 (7.74)	0.0231 (5.5)	0.0224 (4.96)	0.0257 (5.51)	0.0345 (5.84)
Prec. spring sq.	-0.000116 (-5.65)	-0.000142 (-7.11)	-0.000116 (-5.61)	-0.000109 (-4.85)	-0.000108 (-4.79)	-0.000145 (-5.26)
Prec. summer	-0.00621 (-1.6)	-0.0107 (-3.23)	-0.00628 (-1.6)	-0.0101 (-2.37)	-0.0118 (-3.61)	-0.011 (-3.13)
Prec. summer sq.	0.00005 (2.18)	0.0000584 (3)	0.0000366 (1.57)	0.0000632 (2.5)	0.0000706 (3.85)	0.0000692 (3.51)
Prec. autumn	-0.0308 (-5.28)	-0.0305 (-5.16)	-0.0269 (-4.84)	-0.0272 (-4.53)	-0.0305 (-5.32)	-0.0341 (-5.63)
Prec. autumn sq.	0.000148 (4.56)	0.000145 (4.51)	0.000158 (5.06)	0.000147 (4.37)	0.000166 (5.42)	0.00018 (5.57)
Salinity	-0.149 (-1.35)	-0.194 (-1.68)	-0.186 (-1.79)	-0.181 (-1.58)	-0.126 (-1.11)	-0.0809 (-0.638)
Flooding	-0.358 (-3.47)	-0.337 (-2.74)	-0.254 (-2.99)	-0.269 (-2.67)	-0.232 (-1.94)	-0.24 (-2.76)
Wet index	0.337 (5.12)	0.349 (5.49)	0.0323 (0.56)	0.0801 (1.25)	0.0893 (1.24)	0.00817 (0.106)
<i>k</i> factor	-1.32 (-3.36)	-1.03 (-2.56)	-1.08 (-2.88)	-1.2 (-3.33)	-1.74 (-4.7)	-1.48 (-3.66)
Length of slope	0.000394 (3.01)	0.000372 (3.2)	0.000339 (2.74)	0.000332 (2.5)	0.00057 (4.56)	0.000554 (3.86)
Sand	0.422 (2.65)	0.311 (2.38)	0.132 (0.955)	-0.0146 (-0.1)	0.178 (0.972)	0.125 (0.595)
Clay	-0.154 (-1.44)	-0.0141 (-0.178)	0.0998 (1.15)	-0.0269 (-0.324)	-0.208 (-1.87)	-0.199 (-1.43)
Moisture level	4.29 (6.21)	3.67 (4.91)	2.28 (3.75)	2.43 (3.64)	2.76 (3.94)	2.39 (3.43)
Permeability	-0.0555 (-1.47)	-0.02 (-0.74)	-0.0094 (-0.305)	0.0101 (0.362)	-0.0355 (-0.842)	-0.0261 (-0.527)

Table 8.3 (continued)

Model	1978	1982	1987	1992	1997	2002
Income	0.138 (5.32)	0.14 (5.66)	0.0671 (3.64)	0.0713 (3.68)	0.098 (5.28)	0.0858 (5.05)
Income sq.	-3.42E-09 (-4.32)	-3.79E-09 (-5.15)	-9.75E-10 (-2.02)	-1.02E-09 (-2.34)	-1.43E-09 (-3.7)	-1.2E-09 (-3.65)
Density	0.00348 (7.53)	0.00388 (7.19)	0.00373 (7.07)	0.00401 (6.72)	0.00371 (6.41)	0.00421 (6.9)
Density sq.	-0.00000197 (-2.98)	-0.0000024 (-2.87)	-0.00000233 (-2.86)	-0.00000265 (-2.73)	-0.00000268 (-2.88)	-0.0000031 (-3.27)
Constant	10.6 (8.74)	10.8 (8.57)	9.53 (7.83)	11 (8.4)	10 (7.56)	10.5 (7.76)
Adjusted <i>R</i> -squared	0.774	0.759	0.77	0.776	0.788	0.791

Note: *t*-ratio in parentheses.

Because the quadratic form of the climate variables is hard to interpret, we present marginal precipitation and temperature impacts in Table 8.6 for each regression evaluated at the mean US climate. Climate, soil characteristics and other geographical variables tend to be correlated across space. For this reason standard errors are corrected for spatial correlation using Tim Conley's routine (Conley, 1996), with a cutoff point at three degrees. The 95 per cent confidence intervals are reported. With the linear model, the temperature marginal measures the change in dollars per hectare per degree Celsius and the precipitation marginal measures the change in dollars per millimeter per month of precipitation. For the log-normal models, the marginal reflects the percentage increase of land value per degree or millimeter per month.

With the two linear models in Table 8.6, the annual temperature marginals imply that moderate warming is beneficial to US agriculture. However, there is a downward time trend with the temperature marginals. The temperature increase becomes more harmful over time. Although the seasonal marginals are highly significant, they are offsetting. The annual marginal is significant only in 1978 and 1982. Introducing a wider set of counties reduces the temperature marginal. This implies that the counties omitted in the DG data set tend to lie in areas in which global warming might be harmful. The precipitation marginals indicate that a modest increase in seasonal average precipitation increases land values modestly in 1978 and 1982. A wetter climate is highly beneficial in later years. The annual precipitation marginals are more significant than those of temperature. Enlarging the data set does not have a relevant impact on the precipitation marginals and they continue to vary a great deal over time.

Climate marginals are more significant with the log-linear model. The precipitation marginals are very significant even after correcting for spatial correlation. Moderate global warming and a moderate increase of precipitation are beneficial with the log-linear model. The new functional form contributes greatly to reducing the time variability of the precipitation marginals, which now appear not to have a well-defined time trend. The temperature marginals continue to show a downward trend. A series of formal *F*-tests reveals that the log-linear model greatly reduces the variability of the climate coefficients. Although the test rejects the hypothesis that climate coefficients are the same across

Table 8.4 Log-linear model with additional variables

Model	1978	1982	1987	1992	1997	2002
Temp. winter	-0.322 (-11.4)	-0.274 (-9.94)	-0.154 (-5.55)	-0.244 (-8.46)	-0.227 (-8.22)	-0.268 (-9.39)
Temp. winter sq.	-0.00661 (-5.35)	-0.0062 (-4.68)	-0.00345 (-2.7)	-0.00618 (-4.6)	-0.00499 (-3.65)	-0.00453 (-3.14)
Temp. spring	0.379 (5.01)	0.43 (6.11)	0.302 (5)	0.454 (6.34)	0.365 (5.15)	0.301 (3.7)
Temp. spring sq.	-0.00992 (-2.59)	-0.0122 (-3.6)	-0.00884 (-2.62)	-0.0141 (-3.55)	-0.00923 (-2.8)	-0.00527 (-1.25)
Temp. summer	-0.718 (-6.44)	-0.581 (-5.09)	-0.425 (-3.54)	-0.568 (-4.47)	-0.481 (-4.19)	-0.626 (-5.63)
Temp. summer sq.	0.0066 (2.75)	0.00529 (2.2)	0.00441 (1.72)	0.00586 (2.12)	0.00404 (1.73)	0.00513 (2.2)
Temp. autumn	0.312 (1.93)	0.0715 (0.467)	-0.0578 (-0.402)	-0.09 (-0.542)	0.0375 (0.231)	0.306 (1.68)
Temp. autumn sq.	0.0112 (2.03)	0.0156 (3.03)	0.0116 (2.22)	0.0183 (3.08)	0.0127 (2.43)	0.00664 (1.05)
Prec. winter	0.00799 (4.64)	0.00711 (4)	0.00738 (4.24)	0.00801 (4.2)	0.00881 (4.91)	0.00412 (2.15)
Prec. winter sq.	-0.0000207 (-3.17)	-0.0000154 (-2.23)	-0.0000216 (-3.09)	-0.0000148 (-1.99)	-0.0000237 (-3.51)	-0.0000183 (-2.54)
Prec. spring	0.00963 (2.59)	0.0174 (4.78)	0.0106 (2.78)	0.00872 (2.15)	0.0127 (3.24)	0.0187 (4.05)
Prec. spring sq.	-0.0000449 (-2.32)	-0.000101 (-5.35)	-0.0000707 (-3.51)	-0.0000723 (-3.27)	-0.0000668 (-3.27)	-0.0000758 (-3.25)
Prec. summer	0.0073 (1.82)	0.00483 (1.55)	0.00503 (1.33)	0.00273 (0.668)	0.00171 (0.541)	0.00277 (0.821)
Prec. summer sq.	-0.0000076 (-0.342)	0.00000282 (0.165)	-0.0000123 (-0.583)	0.0000108 (0.476)	0.0000143 (0.878)	0.0000112 (0.646)
Prec. autumn	-0.0242 (-5.66)	-0.0213 (-4.98)	-0.0146 (-3.39)	-0.013 (-2.85)	-0.0174 (-4.05)	-0.0193 (-4.41)
Prec. autumn sq.	0.000102 (4.33)	0.0000949 (4.04)	0.0000921 (3.7)	0.0000694 (2.59)	0.0000895 (3.77)	0.0000953 (3.84)
Salinity	-0.0673 (-0.794)	-0.123 (-1.44)	-0.123 (-1.49)	-0.103 (-1.14)	-0.0949 (-1.04)	-0.0189 (-0.186)
Flooding	-0.336 (-3.53)	-0.272 (-2.69)	-0.213 (-2.84)	-0.232 (-2.32)	-0.206 (-2.1)	-0.214 (-2.99)
Wet index	0.408 (7.27)	0.218 (4.19)	-0.0797 (-1.56)	-0.0088 (-0.149)	-0.0244 (-0.401)	-0.0176 (-0.265)
<i>k</i> factor	-0.466 (-1.55)	-0.811 (-2.67)	-0.598 (-2.1)	-1.01 (-3.45)	-1.32 (-4.64)	-1.3 (-3.98)
Length of slope	0.0000346 (0.339)	0.0000399 (0.457)	0.0000343 (0.35)	0.0000421 (0.41)	0.000176 (2.09)	0.000161 (1.55)
Sand	0.275 (1.93)	0.031 (0.286)	-0.0546 (-0.486)	-0.225 (-1.85)	-0.119 (-0.812)	0.0077 (0.0476)
Clay	-0.173 (-2.11)	-0.113 (-1.7)	0.0516 (0.794)	-0.0844 (-1.2)	-0.273 (-3.48)	-0.273 (-2.43)
Moisture level	0.709 (1.18)	0.361 (0.57)	-0.791 (-1.47)	-0.142 (-0.227)	-0.953 (-1.51)	-0.0652 (-0.111)
Permeability	-0.0848 (-2.62)	-0.0322 (-1.5)	-0.0325 (-1.43)	-0.00613 (-0.27)	-0.0545 (-1.72)	-0.0643 (-1.66)

Table 8.4 (continued)

Model	1978	1982	1987	1992	1997	2002
Income	0.00867 (1.58)	-0.00359 (-0.705)	0.0185 (4.54)	0.0163 (3.93)	0.019 (4.48)	0.00361 (0.889)
Density	0.00211 (6.19)	0.0019 (5.43)	0.00203 (5.39)	0.002 (4.5)	0.00146 (3.71)	0.0019 (4.35)
Density sq.	-0.0000011 (-3.02)	-0.00000121 (-2.61)	-0.0000013 (-2.79)	-0.00000135 (-2.45)	-0.00000128 (-2.59)	-0.0000014 (-2.96)
Latitude	-0.00714 (-0.238)	0.00294 (0.112)	-0.0334 (-1.22)	-0.0305 (-0.994)	-0.003 (-0.108)	0.0175 (0.57)
Elevation	-0.000425 (-2.14)	-0.000396 (-2.2)	-0.000557 (-2.88)	-0.000549 (-2.56)	-0.000411 (-2.22)	-0.00043 (-2.21)
Distance met areas	-0.000678 (-6.42)	-0.000831 (-8.1)	-0.000709 (-7.33)	-0.000966 (-9.07)	-0.000896 (-8.6)	-0.000828 (-7.18)
Surface water	0.064 (9.1)	0.0702 (9.4)	0.0698 (8.56)	0.0724 (8.38)	0.0763 (9.32)	0.0756 (8.38)
Share of greenhouses	0.219 (0.925)	0.421 (1.98)	0.447 (2.84)	0.298 (1.47)	0.546 (3.89)	0.229 (1.93)
Government transfers	0.0155 (12.3)	0.0194 (12.1)	0.00292 (12.2)	0.00605 (7.75)	0.0101 (9.95)	0.00368 (8.09)
House price index	0.00608 (7.94)	0.00666 (8.15)	0.00421 (5.24)	0.00504 (6.62)	0.00478 (6.41)	0.0067 (8.15)
Constant	12.1 (4.74)	11.3 (4.9)	12.4 (5.11)	13.3 (4.96)	10.9 (4.73)	10.7 (4.39)
Adjusted R-squared	0.847	0.845	0.842	0.844	0.86	0.867

Note: *t*-ratio in parentheses.

different Census years in both models, while the linear model yields an *F*-ratio equal to 6.22 the *F*-ratio for the log-linear model is equal to 2.76. If we look at temperature and precipitation coefficients separately, we cannot reject the hypothesis that temperature coefficients are the same in the log-linear model (*F*-ratio equal to 1.11) while we reject the hypothesis for the linear model (*F*-ratio equal to 5.81). If we examine climate coefficients by season, we cannot reject the hypothesis that they are the same across Census years for all seasons in the log-linear model, while in the linear model we reject the null hypothesis for all seasons but spring (at the 10 per cent confidence level).

Introducing a wider set of control variables in the log-linear model produces more stable temperature marginals. In particular, the time trend that appears in the DG estimates disappears. We greatly reduce the time variation of climate marginals by controlling for variables such as the value of residential properties and the increase in greenhouses.

Importantly, the log-linear model with additional variables shows that even moderate global warming is harmful though not significant. Additional precipitation remains beneficial. The value of increased availability of surface water is highly beneficial. An average increase of one millimeter of rain is roughly two to three times more beneficial than an equivalent increase of surface water.

Table 8.5 Ratio of predicted to actual value of land by decile for Ricardian models in Tables 8.2, 8.3 and 8.4

		Deciles								
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th
1978	Linear	0.975	1.148	1.131	1.137	1.119	1.087	1.067	1.024	0.937
	Log-linear	1.065	0.957	0.994	0.988	0.970	0.945	0.937	0.924	0.896
	Log-linear Adv.	1.020	1.022	1.047	1.079	1.073	1.057	1.026	1.024	1.016
1982	Linear	1.124	1.212	1.168	1.130	1.086	1.043	1.015	0.969	0.890
	Log-linear	1.072	0.980	1.022	0.997	0.968	0.934	0.920	0.900	0.862
	Log-linear Adv.	1.031	1.017	1.040	1.051	1.040	1.037	1.033	1.028	1.026
1987	Linear	1.032	1.114	1.130	1.145	1.108	1.061	1.009	0.937	0.889
	Log-linear	1.039	0.964	0.995	1.005	0.982	0.955	0.922	0.880	0.834
	Log-linear Adv.	1.011	0.988	1.065	1.031	1.032	1.054	1.047	1.030	1.026
1992	Linear	0.988	1.159	1.134	1.129	1.121	1.081	1.025	0.960	0.889
	Log-linear	1.058	0.958	0.978	0.985	0.965	0.940	0.907	0.882	0.830
	Log-linear Adv.	1.020	1.004	1.075	1.039	1.040	1.046	1.049	1.022	1.011
1997	Linear	0.930	1.149	1.131	1.146	1.135	1.084	1.014	0.934	0.869
	Log-linear	1.061	0.938	0.931	0.970	0.958	0.938	0.900	0.865	0.848
	Log-linear Adv.	1.014	0.997	1.074	1.037	1.042	1.040	1.043	1.043	1.023
2002	Linear	0.946	1.159	1.080	1.092	1.112	1.063	1.000	0.941	0.890
	Log-linear	1.065	0.933	0.895	0.927	0.928	0.904	0.883	0.873	0.859
	Log-linear Adv.	1.009	1.006	1.094	1.064	1.051	1.059	1.064	1.050	1.024

Note: The linear model corresponds to column (4) of Table 8.6, the log-linear model corresponds to column (5) and the log-linear with additional variables (6).

AGGREGATE WELFARE IMPACTS

In order to evaluate larger changes in climate, we explore three climate scenarios for the 48 lower states. The first scenario assumes a uniform temperature and precipitation increase of +2.7 °C (+5 °F) and 8 per cent, respectively. This scenario, despite being overly simplistic, is a widely used benchmark in the literature representing what was once thought to be the outcome of doubling CO₂ concentrations. We also use two detailed climate change scenarios for 2100: the Parallel Climate Model (PCM) (National Center for Atmospheric Research) and HadCM3 (Hadley Centre). The emission scenario underlying the two climate projections is the SRES A2 scenario (Nakićenović et al., 2000), which predicts atmospheric concentrations of greenhouse gases equal to 850 ppme (CO₂ equivalents) by 2100. Changes in temperature are computed by subtracting the normals for 1961–90 from the climate normals for 2070–99 from each model. The changes in precipitation are computed taking the precipitation normal for 2070–99 and dividing it by the precipitation normal for 1961–99 from each model. In contrast, DG mistakenly took the predicted climate normal from the model and subtracted the actual

Table 8.6 Annual temperature and precipitation marginals at mean US climate

	Basic model	More counties	log-linear	Log-linear with additional variables
Temperature (°C)	(\$2000 per ha)	(\$2000 per hectare)	(% of land value per ha)	(% of land value per ha)
1978	206.5 *** (112.3, 300.7)	161.9 *** (69.3, 254.5)	4.21 *** (1.6, 6.8)	0.2 (-8.71, 9.11)
1982	143.7 *** (43.8, 243.6)	92.9 ** (0.2, 185.6)	3.38 *** (0.7, 6.1)	-0.3 (-8.5, 7.9)
1987	52.8 (-12, 117.6)	39.4 (-23, 101.8)	2.98 *** (0.3, 5.7)	-4.5 (-12.35, 3.35)
1992	63.5 (-25.3, 152.3)	30.6 (-49.6, 110.8)	2.61 ** (-0.6, 5.8)	-4.5 (-13.8, 4.8)
1997	66.6 (-29, 162.2)	27.6 (-60.7, 115.9)	1.5 (-1.6, 4.6)	-1.7 (-10.64, 7.24)
2002	-6.2 (-116.2, 115.6)	-31.8 (-134.1, 70.5)	-0.27 (-3.9, 3.3)	-1 (-10.12, 8.12)
Precipitation (mm)	(\$2000 per ha)	(\$2000 per hectare)	(% of land value per ha)	(% of land value per ha)
1978	2.9 (-10.8, 16.6)	1.2 (-12.5, 15)	0.75 *** (0.4, 1.1)	0.4 *** (0.07, 0.79)
1982	6.1 (-5.2, 17.5)	3.4 (-7.8, 14.7)	0.57 *** (0.2, 0.9)	0.3 *** (-0.02, 0.68)
1987	14.7 *** (5.6, 23.7)	13.8 *** (5.3, 22.4)	0.78 *** (0.5, 1.1)	0.5 *** (0.19, 0.81)
1992	12.2 ** (1.7, 22.7)	11.3 ** (1.4, 21.3)	0.86 *** (0.5, 1.2)	0.4 *** (0.07, 0.81)
1997	12.9 *** (3.1, 22.6)	13.2 *** (3.8, 22.6)	1.08 *** (0.7, 1.4)	0.7 *** (0.37, 1.07)
2002	11.6 (-4.6, 27.8)	14.6 ** (0.3, 28.9)	1.13 *** (0.8, 1.5)	0.7 *** (0.36, 1.08)
Surface water (liters per day / ha)	(\$2000 per ha)	(\$2000 per hectare)	(% of land value per ha)	(% of land value per ha)
1978				6.4 ** (4.86, 7.94)
1982				7.02 ** (5.44, 8.6)
1987				6.98 ** (5.23, 8.73)
1992				7.24 ** (5.48, 9)
1997				7.63 ** (5.84, 9.42)
2002				7.56 ** (5.67, 9.45)

Note: Standard errors corrected for spatial correlation, cutoff point at 3 degrees. Significance level:

* $p < 0.01$; ** $p < 0.05$; *** $p < 0.01$.

climate normal from observed data (Fisher et al., 2011). The climate change variable used in DG mixes the predicted change by the climate model with the difference between the model's predictions and actual observed climate.

In order to interpolate from the grid zones used by the climate models to counties, we interpolate from the center of the four closest grid zones to each county. We weight each observation by the inverse squared distance from the county's geographic center to the center of each grid. By interpolating the data from the climate models, we obtain a smooth scenario of climate change for the 48 lower states at a county-level resolution. We create weighted temperature changes for the 12 months and add them to the observed monthly climate temperature. We then take the weighted ratio of precipitation and multiply it by the observed precipitation level for each county. The new seasonal climate variables for the end of the century are created by taking the arithmetic average of the monthly climate variables under the new climate. For example, for the HadCM3 climate model, the temperature normal for month m , at county i , under the new climate C_1 at 2100, is computed as follows:

$$t_{had,i,m} = t_{0,i,m} + \delta_{had,i,m} \quad (8.10)$$

The HadCM3 scenario predicts much higher average increases in temperature, higher temperature variance and drier summers than the PCM scenario. Both scenarios imply an average increase in temperature that is higher than the Uniform benchmark scenario.

The two climate models also predict very different outcomes across space. HadCM3 predicts the largest temperature increases in the central states, with a strong increment in the Rocky Mountains and in northern Wisconsin and Minnesota. PCM predicts larger temperature increases in the west coast and in the north just below the Canadian border. The regional distribution of precipitation change is also different. The HadCM3 scenario forecasts wetter winters in Montana, the Dakotas and northern Minnesota and Wisconsin. Texas, California, Georgia, Alabama and northern Florida are all expected to become drier. The Mississippi Valley and the arid southwest are predicted to get wetter winters. The PCM scenario is radically different. The USA will in general be a drier place in winter, with only central-northern states and central-southern states experiencing some increases in precipitation.

The regional distribution of climate changes is a key determinant of the final estimate of the welfare impact of climate change on US agriculture. The three selected models offer a wide range of possible future climate patterns and are thus suited to test the robustness of the estimates of welfare impacts of climate change on US agriculture.

We next examine the impact of each climate scenario. The uniform change scenario is the easiest scenario to interpret (because the climate change is uniform across space). We report 95 per cent confidence intervals for all welfare estimates. Standard errors have been corrected for spatial correlation. The confidence intervals have been obtained by bootstrapping.

With the uniform scenario in Table 8.7, we begin with the estimated welfare results from DG in column 1. There is a clear time trend from a net benefit of \$154 billion in 1978 to a loss of \$110 billion in 2002. As we correct the model, however, the results change. In column 2 we estimate the welfare results for the same model except that we

Table 8.7 Welfare impact on US agriculture – Uniform climate change scenario

Model	DG	Basic model	Expected farmland	More counties	Log-linear	Log-linear with additional variables
	(1)	(2)	(3)	(4)	(5)	(6)
1978	154.70	134.1 *** (56.8, 211.5)	128.5 *** (55.3, 201.7)	137 *** (36.1, 237.9)	281.5 *** (151.3, 391.8)	127.3 (-572, 1063.2)
	15.0%	13.0%	16.0%	13.4%	27.5%	12.5%
1982	40.80	101.6 ** (22.2, 181)	99.6 ** (22, 177.1)	92.7 * (-8.9, 194.3)	190.7 *** (82.6, 276.5)	98.3 (-565.7, 1082.2)
	4.3%	10.7%	12.4%	9.1%	18.7%	9.6%
1987	-8.70	25.6 (-22.7, 73.9)	25.3 (-23.3, 73.8)	36.5 (-33, 106)	112.5 *** (30.3, 168.3)	-52.3 (-277.7, 242.2)
	-1.3%	4.0%	3.1%	3.6%	11.0%	-5.1%
1992	-8.10	34.2 (-33, 101.5)	35.4 (-33.7, 104.5)	33 (-60.8, 126.9)	101.9 *** (15.9, 165.5)	-50.4 (-308.5, 340.8)
	-1.3%	5.5%	4.4%	3.2%	10.0%	-4.9%
1997	-33.50	22.5 (-46.3, 91.3)	23.9 (-47.4, 95.3)	13 (-83.2, 109.2)	90.1 *** (13.9, 149.8)	15.2 (-310.4, 452.5)
	-4.7%	3.2%	3.0%	1.3%	8.8%	1.5%
2002	-101.00	-46.7 (-129.3, 35.8)	-48.5 (-132.8, 35.8)	-54.9 (-167.2, 57.4)	47.7 (-54.5, 120.4)	37.6 (-281.7, 494.2)
	-11.7%	-5.4%	-6.0%	-5.4%	4.7%	3.7%

Notes: All dollar figures are in billions of US\$2000. Welfare impacts correspond to a uniform increase of temperature of 2.7 °C and of 8 per cent of precipitation. 95 per cent confidence intervals in parentheses. Significance level: * $p < 0.01$; ** $p < 0.05$; *** $p < 0.01$. Confidence intervals for the log-linear and the log-linear with additional variables models are bootstrap estimates with 10000 repetitions.

include an improved set of climate variables. Correcting the climate errors in DG makes a large difference in the welfare estimates (Fisher et al., 2010). In column 3, we calculate welfare using the expected level of farmland. Although there are large changes in the amount of farmland in each county across time, holding farmland constant makes only a small difference in the aggregate welfare estimates. In column 4 we expand the sample to include almost all agricultural counties in the USA. Expanding the data set to include almost all agricultural counties also makes a minor difference.

Column 5 changes the functional form of the model from linear to log-linear. The log-linear functional form predicts much larger benefits from warming and slightly increases the range of results across years. Estimates are very significant over all but one census year. The sixth column in Table 8.7 includes more variables that explain why land values vary (greenhouses, subsidies, home values and surface water withdrawals) vary. Adding more explanatory variables to the log-linear model reduces the size of the benefits and also the range of estimates across time. However, there remains a large difference in results across each regression. Specifically there are large benefits in the first two time periods, damages in the next two period and small benefits in the last two periods. Adding new variables to the basic log-linear model reduces the significance of welfare estimates.

Table 8.8 Welfare impact on US agriculture – HadCM3 climate scenario

Model	Basic model	Expected farmland	More counties	Log-linear	Log-linear with additional variables
	(2)	(3)	(4)	(5)	(6)
1978	119.4 (-252.2, 491) 11.6%	108.8 (-245.1, 462.6) 13.5%	-190.3 (-662.2, 281.6) -18.6%	583.3 * (-3.6, 1284.2) 57.1%	-101.1 (-1207.4, 1700.7) -9.9%
1982	132.2 (-232.9, 497.2) 13.9%	129.1 (-229.1, 487.2) 16.1%	-150 (-618.9, 318.9) -14.7%	530.9 * (5.5, 1135) 51.9%	-73.9 (-1143.1, 1733.7) -7.2%
1987	-58.8 (-284.8, 167.3) -9.1%	-58.2 (-284.5, 168.2) -7.2%	-153.4 (-469.1, 162.2) -15.0%	230.1 (-129.8, 580.2) 22.5%	-81.7 (-465.4, 472.4) -8.0%
1992	35.1 (-314.1, 384.4) 5.6%	39.5 (-317.5, 396.4) 4.9%	-143 (-586.7, 300.7) -14.0%	235.1 (-150.7, 662.6) 23.0%	-71.5 (-549.7, 805.5) -7.0%
1997	-84.5 (-436.8, 267.8) -11.9%	-85.4 (-449, 278.3) -10.6%	-351.3 (-809.6, 107.1) -34.4%	81.8 (-202.7, 409.8) 8.0%	-86.1 (-574.2, 610.7) -8.4%
2002	-412.5 * (-866.6, 41.5) -47.7%	-419.2 * (-882.1, 43.7) -52.1%	-702.7 ** (-1262.1, -143.3) -68.8%	-150.2 (-460.9, 186.1) -14.7%	-170.4 (-648.1, 723.6) -16.7%

Notes: All dollar figures are in billions of US\$2000. Welfare impacts correspond to the HADLEY climate scenario. 95 per cent confidence intervals in parentheses. Significance level: * $p < 0.01$; ** $p < 0.05$; *** $p < 0.01$. Confidence intervals for the log-linear and the log-linear with additional variables models are bootstrap estimates with 10000 repetitions.

Table 8.8 displays the welfare impacts of the HadCM3 climate model for 2100. When more counties are added to the data set (column 4 rather than column 3), the welfare estimates change dramatically from very positive to very negative. In addition, welfare impacts measured in percentages of total land values in the USA change abruptly. The estimates also have wide confidence intervals and are not significant.

Table 8.8 also reveals that the choice of the functional form has great relevance for the sign and magnitude of welfare impacts. Column 5 again reverts the sign of welfare impacts with respect to column 4. Column 4 has the largest number of significant estimates. The log-linear model with additional variables changes the story again and shows both moderate, non-significant, positive or negative impacts of climate change.

Table 8.9 presents welfare estimates obtained using the PCM climate change scenario. The first message to draw from Table 8.9 is that the same set of climate coefficients can deliver both significant and insignificant welfare estimates, depending on the climate scenario used. If the climate scenario changes a season with significant (insignificant) climate coefficients, the resulting welfare impact estimates will be significant (insignificant). The welfare estimates also have different patterns over time with each climate scenario. Compared to the Uniform and the HadCM3 climate change scenarios, the PCM

Table 8.9 Welfare impact on US agriculture – PCM climate scenario

Model	Basic model	Expected farmland	More counties	Log-linear	Log-linear with additional variables
	(2)	(3)	(4)	(5)	(6)
1978	532.8 *** (364, 701.5) 51.6%	499.9 *** (341.9, 658) 62.2%	595.3 *** (384.8, 805.8) 58.3%	984.4 *** (593.6, 1417.5) 96.3%	946 ** (-161.6, 2758.7) 92.6%
1982	363.5 *** (212.1, 514.9) 38.3%	353.8 *** (206.9, 500.7) 44.0%	398.7 *** (205.3, 592.1) 39.0%	663.5 *** (363.4, 944.6) 64.9%	662.1 ** (-282.3, 2261.2) 64.8%
1987	190.3 *** (93.6, 287.1) 29.5%	191.8 *** (94.6, 289.1) 23.9%	209.3 *** (79.1, 339.6) 20.5%	404.2 *** (196.4, 595.7) 39.6%	33.2 (-278, 444.4) 3.2%
1992	224.9 *** (101.4, 348.5) 36.1%	232.7 *** (105.4, 359.9) 28.9%	225.6 *** (67.7, 383.4) 22.1%	454.1 *** (215.9, 671.4) 44.4%	140.2 (-260.7, 804.6) 13.7%
1997	267.3 *** (122.5, 412) 37.5%	277.4 *** (126.7, 428.1) 34.5%	256.6 *** (67.6, 445.5) 25.1%	426 *** (218.6, 642.2) 41.7%	213.8 (-247.2, 825.2) 20.9%
2002	246.8 ** (58.8, 434.9) 28.6%	249.1 ** (56.6, 441.6) 31.0%	215 * (-11.5, 441.4) 21.0%	433.5 *** (150.2, 719.3) 42.4%	293.3 * (-169.7, 976.5) 28.7%

Notes: All dollar figures are in billions of US\$2000 USD. Welfare impacts correspond to the PCM climate scenario. 95 per cent confidence intervals in parentheses. Significance level: * $p < 0.01$; ** $p < 0.05$; *** $p < 0.01$. Confidence intervals for the log-linear and the log-linear with additional variables models are bootstrap estimates with 10000 repetitions.

scenario shows that climate change is expected to be largely beneficial for US agriculture due to the more moderate temperature and precipitation increases.

Although it is helpful to know the aggregate impact of each climate scenario, the aggregate figures hide the substantial variation of impacts across the country. Figure 8.2 (see p. 250) displays the impacts in each county caused by the uniform climate change scenario. Although the change in climate is the same for every county in this scenario, the agricultural impacts are not the same. The northeast and north-central regions are predicted to have large gains. Most of the great plains and southeast will have small benefits. The western regions will experience small damages and the Pacific coast will experience large damages.

Figure 8.3 (see p. 251) displays the results of the HadCM3 climate scenario. The HadCM3 model predicts benefits in the southeastern USA. There are also benefits in the northern states of Minnesota and North Dakota. However, there are strong damages stretching from the northeast to the entire western region of the USA.

Figure 8.4 (see p. 252) displays the results of the PCM climate scenario. The entire eastern and central regions of the USA benefit in this scenario. The damages are limited to the west and are more severe in the northwest.

CONCLUSIONS

The analysis conducted above consistently finds that climate affects farmland value in the USA. In all the models, the climate coefficients are significant. However, the climate coefficients are sensitive to the inclusion of additional control variables (enhanced model) and to the functional form.

The analysis was repeated for different census years from 1978 through 2002. As found by Deschenes and Greenstone (2007), the results vary across years. In the first two periods of data (1978, 1982), the analyses suggest that the marginal effect of temperature is positive, but in the remaining four periods (1987–2002) it is negative. In contrast, the marginal effect of precipitation was generally positive across every year.

Examining future climate scenarios reveals that the results vary by scenario and econometric model. For the linear and enhanced linear models, the Uniform and HadCM3 climate scenarios are predicted to be harmful using data from 1987 onward but beneficial using data from 1978 and 1982. In contrast, with the log-linear model these climate scenarios were predicted to generate small benefits. With the PCM climate scenario all models and almost all years predict a beneficial outcome for the USA. These results suggest that if climate change is mild, it will probably be beneficial for USA farmers. However, if climate change turns out to be more severe, there may well be large losses across US farms.

The fact that the results depend upon the functional form suggests that the Ricardian literature needs to be more careful in deciding what functional form to choose. Analysts should be careful to determine which functional form most closely fits the data. The fact that the results also vary depending on the control variables suggests that analysts must also work hard to include all relevant variables. Underspecified models can lead to seriously biased estimates. Finally, the year of data also matters. These results imply that there are still missing variables that explain why farmland prices vary across time and that these variables affect the climate coefficients. Massetti and Mendelsohn (2011) expand the analysis in this chapter and show that panel data methods successfully eliminate any time trend in the variance of the climate coefficients but reject the hypothesis that climate coefficients are stable over time. More research is clearly needed to try to reduce the range of results across years.

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DATA APPENDIX

We have constructed a balanced panel with observations for 2914 counties in the contiguous 48 states over the years 1978, 1982, 1987, 1992, 1997 and 2002. Units of measurement are in the metric system; economic variables have all been converted to constant 2000 US dollars using the GDP deflator. If not otherwise stated, variables measure data of interest in years 1978, 1982, 1987, 1992, 1997 and 2002.

Time-varying, County-specific Socioeconomic Variables

Farmland value

Estimated value of land and buildings, average per hectare of farmland. Data source is the Agricultural Census.

Farmland

Land in farms as in the Census of Agriculture from 1978 to 2002, hectares. The Census of Agriculture defines 'Land in farms' as agricultural land used for crops, pasture or grazing. It also includes woodland and wasteland not actually under cultivation or used for pasture or grazing, provided it was part of the farm operator's total operation. Large acreages of woodland or wasteland held for non-agricultural purposes were deleted from individual reports. Land in farms includes acres in the Conservation Reserve and Wetlands Reserve Programs. Land in farms is an operating unit concept and includes land owned and operated as well as land rented from others.

Income

Per capita personal income (\$); Bureau of Economic Analysis, Regional Economic Accounts, table CA1-3.

Density

Population per square kilometer. Data on population are from the Bureau of Economic Analysis, Regional Economic Accounts, table CA1-3.

Greenhouses

Share of total crop sales from nursery, greenhouse and floriculture. *Source:* Census of Agriculture.

Subsidies

Government payments per hectare of land (\$). *Source:* Census of Agriculture.

Real estate

Median value for all owner-occupied housing units (\$1000). Census of Population and Housing, 1980, 1990 and 2000. Values for panel years have been computed extrapolating linear trends from the three census years available.

Permeability

The minimum value for the range in permeability rate for the soil layer or horizon, expressed as inches/hour.

Time-invariant, County specific Geographic Variables

Latitude

Latitude of county's centroid in decimal degrees.

Elevation

Elevation of county's centroid in meters.

Distance from metropolitan areas

Distance in kilometers between county's centroid and metropolitan areas with more than 200 000 inhabitants in 2000.

Surface water withdrawal

Thousands of liters per day, per hectare, of surface fresh water for irrigation purposes. The 'Estimated use of water in the United States', published every five years by the US Geological Survey, supplies data on water use at county level only starting from 1985. We divided the amount of water used at county level for years 1985, 1990, 1995, 2000 by the amount of farmland in that county in census years 1987, 1992, 1997 and 2002, respectively, and we computed the time average of surface water use per hectare of land. We used this variable as a proxy for surface water availability at county level for all time observations of our panel.

Time-invariant, County-specific Climate Variables

Climate variables

We have estimated a quadratic climate surface for the contiguous 48 states following the approach described in Mendelsohn et al. (1994). The data source for climate normals is the National Climatic Data Center CLIM81 series, which contains monthly station normals (1971–2000) for 7467 weather stations in the contiguous 48 states, of which 2135 provide only precipitation data. For each county we select weather stations contained in a 500-mile radius centered at county's centroid, and we estimate local monthly climate by applying weighted least squares to a quadratic combination of stations' longitude, latitude, elevation and distance from coastline; as weights we use the squared distance between the county's centroid and the weather station. Seasonal climate is obtained as the arithmetic average of climate variables in winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Temperatures are measured in degrees Celsius and precipitation is measured in millimeters.

Time invariant, County-specific Soil Characteristics

Salinity

Percentage of agricultural land that has salinity–sodium problems.

Flooding

Percentage of agricultural land occasionally or frequently prone to flooding.

Wet factor

Percentage of agricultural land that has very low drainage (poor and very poor).

***k* factor**

Average soil erodibility factor. It is the average soil loss in tons/acre, a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff.

Slope length

Average slope length factor in feet.

Sand

Percentage of agricultural land classified as sand or coarse-textured soils.

Clay

Percentage of agricultural land that is classified as clay.

Moisture level

Minimum value for the range of available water capacity for the soil layer or horizon, expressed as inches/inch.

PART III

AGRICULTURAL IMPACTS ON THE ECONOMY

9 Economy-wide impacts of climate change on agriculture – case study for adaptation strategies in sub-Saharan Africa

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Richard S.J. Tol and Claudia Ringler*

INTRODUCTION

Agriculture is by far the largest consumer of freshwater resources. Globally, around 70 per cent of all available freshwater is used for irrigation (United Nations, 2003). While irrigated agriculture focuses on withdrawals of water from surface and groundwater sources, rainfed agriculture relies on soil moisture generated from rainfall. In many developing countries the agricultural sector provides the main livelihood and employment for the majority of the population and contributes considerably to national GDP. Therefore reductions in agricultural production caused by future climate change could seriously weaken food security and worsen the livelihood conditions for the rural poor (Commission for Africa, 2005).

Climate change will affect agricultural productivity through different mechanisms. The *World Development Report 2008* (World Bank, 2007) identifies five main factors: changes in temperature; changes in precipitation; changes in carbon dioxide (CO₂) fertilization; increased weather variability; and changes in surface water runoff. Crop production is directly influenced by precipitation and temperature. Precipitation determines the availability of freshwater and the level of soil moisture. Temperature and soil moisture determine the length of the growing season and control the crop's development and water requirements. Weather variability, especially changes in rainfall patterns, is particularly important for rainfed agriculture. Soil moisture limitations reduce crop productivity and increase the risk of rainfed farming systems. Although the risk of climate variability is reduced by the use of irrigation, irrigated farming systems depend on reliable water sources that may be exposed to changes in the spatial and temporal distribution of river flow (CA, 2007) as a result of climate change. A positive effect on crop production is expected by higher atmospheric concentrations of carbon dioxide (CO₂ fertilization), which can enhance plant growth and increase water use efficiency.

Both partial and general equilibrium models have been used to analyze climate change impacts on agriculture. While partial equilibrium analyses focus on the sector affected by a policy measure assuming that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine economy-wide effects. Most studies using general equilibrium models focus on the national level. However, farmers operate, directly or indirectly, in world markets for agricultural products. Moreover, climate change impacts agricultural productivity and hence modifies regional comparative advantages, and hence regional trade patterns and welfare. This

chapter therefore focuses on the impacts of climate change on agriculture in the context of international trade and analyzes the role of adaptation in adjusting to new climate conditions in sub-Saharan Africa. We use a combination of a partial equilibrium model (IMPACT) and a general equilibrium model (GTAP-W) to assess both changes in agricultural productivity and production as a result of climate change, as well as economy-wide impacts.

IMPACT (Rosegrant et al., 2002) is a partial agricultural equilibrium model that allows for the combined analysis of water and food supply and demand. Based on a loose coupling with a global hydrologic model, climate change impacts on water and food can be analyzed as well (Zhu et al., 2008). The GTAP-W model (Calzadilla et al., 2011) is a global computable general equilibrium (CGE) model that allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications of alternative development pathways. Unlike an earlier version GTAP-W (Berrittella et al., 2007), the revised GTAP-W model distinguishes between rainfed and irrigated agriculture.

This chapter is organized as follows. It first reviews economic models of water use as well as some of the models that have been used to assess water and the impact of climate change on food production and welfare, and then describes in detail one such modeling framework, GTAP-W, which has been used together with IFPRI's IMPACT model to analyze the impacts of climate change on water and food supply and demand and welfare. The chapter continues by analyzing the role of adaptation to new climate conditions in sub-Saharan Africa.

ECONOMIC MODELS OF WATER USE

Economic models of water use have generally been applied to look at the direct effects of water policies such as water pricing or quantity regulations on the allocation of water resources. In order to obtain insights from alternative water policy scenarios on the allocation of water resources, partial and general equilibrium models have been used, among others. While partial equilibrium analyses focus on the sector affected by a policy measure, assuming that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine economy-wide effects; partial equilibrium models tend to have more detail, at least in the sector under consideration.

Most of the studies using either of the two approaches analyze pricing of irrigation water only (for an overview of this literature see Johannson et al., 2002). Rosegrant et al. (2002) use IMPACT to estimate demand and supply of food and water to 2025. De Fraiture et al. (2004) extend this to include virtual water trade using cereals as an indicator. Their results suggest that the role of virtual water trade is modest. While IMPACT covers a wide range of agricultural products and regions, non-agricultural sectors are excluded.

Studies of water use using general equilibrium approaches are generally based on data for a single country or sub-national region, assuming no effects for the rest of the world from the implemented policy (for an overview of this literature see Dudu and Chumi, 2008). Decaluwé et al. (1999) analyze the effect of water pricing policies on demand and supply of water in Morocco using an extended CGE model, which explicitly models dif-

ferent technologies in water production, differentiating between southern and northern regions. Diao and Roe (2003) use an intertemporal CGE model for Morocco focusing on both the short-term and the long-term transitional dynamic effects of trade reforms and a water-user rights market. Their model differentiates rainfed and irrigated sectors and water is modeled as a factor of production. Diao et al. (2008) extend that model to analyze groundwater resources and rural–urban water transfer in Morocco. Seung et al. (2000) use a county-level dynamic CGE model with a recreation demand module to estimate the welfare gains of reallocating water from agriculture to recreational use for the Stillwater National Wildlife Refuge in Nevada. Letsoalo et al. (2007) and van Heerden et al. (2008) study the effects of water charges on water use, economic growth and the real income of rich and poor households in South Africa. Using a county-level dynamic CGE model for the Arkansas River Basin, Goodman (2000) shows that temporary water transfers are less costly than building new dams. Strzepek et al. (2008) estimate the economic benefits of the High Aswan Dam. Gómez et al. (2004) analyze the welfare gains by improved allocation of water rights for the Balearic Islands. Water is a factor of production used by farmers and the water supply firms, which owns some concessional water rights. Feng et al. (2007) use a two-region recursive dynamic general equilibrium approach based on the GREEN model (Lee et al., 1994) to assess the economic implications of the increased capacity of water supply through the Chinese South-to-North Water Transfer (SNWT) project.

All of these CGE studies have a limited geographical scope. Berittella et al. (2007) and Calzadilla et al. (2010a, 2011) are exceptions. Using a previous version of the GTAP-W model, Berrittella et al. (2006, 2007, 2008a and 2008b) analyze the economic impact of various water resource policies. Unlike the predecessor GTAP-W, the revised GTAP-W model used in this study distinguishes between rainfed and irrigated agriculture. The new production structure of the model introduces water as an explicit factor of production and accounts for substitution possibilities between water and other primary factors.

Calzadilla et al. (2011) use the global CGE model GTAP-W, which accounts for water resources use in the agricultural sector to analyze the economy-wide impacts of enhanced irrigation efficiency. They find that regional and global water savings are achieved when irrigation efficiency improves. World regions where irrigation efficiency improves save water, but other world regions are able to conserve water as well. The authors show mostly positive welfare gains for water-stressed regions; for non-water-scarce regions welfare gains are more mixed and mostly negative. Calzadilla et al. (2010a) use the same model to investigate the role of green (rainfall) and blue (irrigation) water resources in agriculture. They evaluate different scenarios of sustainable water use in the agricultural sector, and find a clear tradeoff between economic welfare and environmental sustainability.

Country CGE models tend to have more detail in terms of sectors and household types, and hence they are more suitable for country-specific policy analysis (e.g. the effects of different pricing schemes on the distribution of income among different population groups). Global CGE models tend to have less sectoral detail and only one representative household. Therefore global CGE models are more suitable for the analysis of multilateral policies (e.g. implications of trade liberalization and climate change policies like the Kyoto Protocol).

ECONOMIC MODELS APPLIED TO CLIMATE CHANGE ANALYSIS

Despite the global scale of climate change and the fact that food products are traded internationally, climate change impacts on agriculture have mostly been studied at the farm level (for example Abler et al., 1998), the country level or at the level of world regions (for example Verburg et al., 2008). Early studies of climate change impacts on global agriculture analyzed the economic effects of doubling the atmospheric carbon dioxide (CO₂) concentration based on alternative crop response scenarios with and without CO₂ effects on plant growth. Results indicate that the inclusion of CO₂ fertilization is likely to offset some of the potential welfare losses generated by climate change (Kane et al., 1992; Reilly et al., 1994; Rosenzweig and Parry, 1994; Tsigas et al., 1997; Darwin and Kennedy, 2000).

These studies did not analyze adaptation options. However, global CGE models that capture regional changes in agricultural inputs and managements options avoid these limitations. Darwin et al. (1995) use the Future Agricultural Resources Model (FARM) to study the role of adaptation in adjusting to new climate conditions. The FARM model differentiates six land classes according to the length of the growing season and is composed of a global CGE model and a geographic information system that links climate with production possibilities at the world regional level. The results suggest that farm-level adaptations might mitigate any negative impacts induced by climate change. In a more recent analysis, Darwin (2004) suggests that world regions with a relatively large share of income from agricultural exports may be vulnerable not only to direct climate-induced agricultural damages, but also to positive impacts induced by greenhouse gas emissions elsewhere.

Based on the general equilibrium basic linked system (BLS) model, Fischer et al. (1994, 1996) study the potential biophysical responses of major food crops to a doubling of CO₂ concentrations, as well as the socioeconomic consequences for the period 1990–2060. The BLS model comprises a series of national and regional agricultural economic models that are linked together by means of a world market, where international clearing prices are computed to equalize global demand with supply. Parry et al. (1999) use the same model to look at the world's food security, estimating that climate change may increase the number of people at risk of hunger by around 80 million people in 2080. The BLS model has been used in conjunction with the agro-ecological zone (AEZ) model to analyze potential impacts of climate change in agro-ecological and socioeconomic systems up to 2080 (Fischer et al., 2005; Fischer et al., 2007; Tubiello and Fischer, 2007). The AEZ modeling framework uses detailed agronomic-based knowledge to simulate land resources availability and use, farm-level management options and crop production potentials. The results suggest regional and temporal asymmetries in terms of impacts due to diverse climate and socioeconomic structures. Adaptations on farm and via market mechanisms are going to be important contributors to limiting the severity of impacts. Mitigation efforts may reduce the global cost of climate change and reduce the number of additional people at risk of malnutrition. None of these studies has water as an explicit factor of production. An exception is Calzadilla et al. (2010b). They use the GTAP-W model to assess potential impacts of climate change and CO₂ fertilization on global agriculture, based on predicted changes in the magnitude and distribution of

global precipitation, temperature and river flow for the IPCC SRES A1B and A2 scenarios (IPCC, 2000). By introducing irrigation water as a factor of production, Calzadilla et al. (2010b) are able to account for changes in river flow, and hence in water supply for irrigated crops. The distinction between rainfed and irrigated farms is crucial because rainfed and irrigated agriculture face different climate risk levels. The results show that global food production, welfare and GDP are expected to fall under both SRES scenarios. Countries are not only influenced by regional climate change but also by climate-induced changes in competitiveness. The authors' results further suggest that a partial analysis of the main factors through which climate change will affect agricultural productivity lead to different outcomes. For instance, when changes in precipitation and water supply are considered to impact agricultural yields, global welfare losses are less than half of the expected reduction when only precipitation is considered.

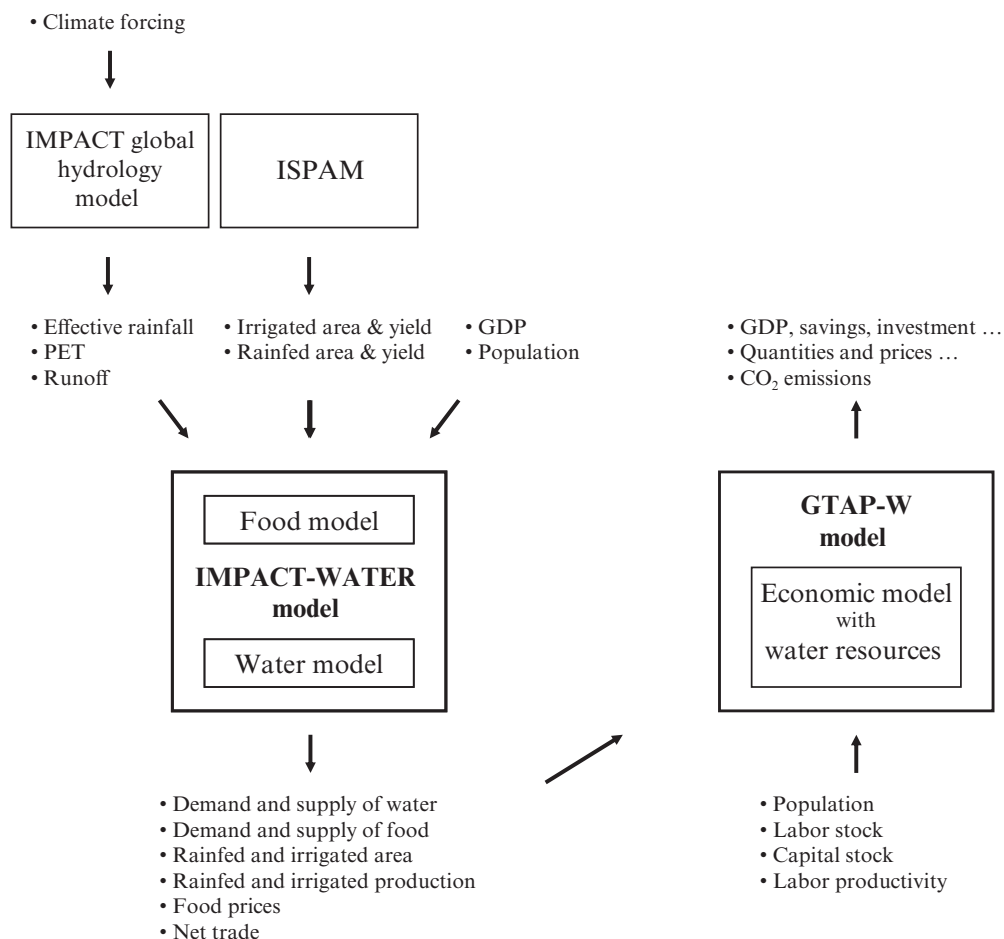
MODELING FRAMEWORK

The extensions to the GTAP-W model are partially based on information from IMPACT (for more details see Calzadilla et al., 2011). GTAP-W uses information about the demand and supply of water, demand and supply of food, rainfed and irrigated production, and rainfed and irrigated area to modify the social accounting matrices for the individual world regions, and calibrate the model to the new data set based on 2001. Figure 9.1 shows the links between IMPACT and GTAP-W and the main driving forces behind both models.

IMPACT

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was developed at the International Food Policy Research Institute (IFPRI) in the early 1990s, upon the realization that there was a lack of long-term vision and consensus among policy makers and researchers about the actions necessary to feed the world in the future, reduce poverty and protect the natural resource base (Rosegrant et al., 2005). IMPACT encompasses most countries, world regions and the main agricultural commodities produced in the world. As a partial equilibrium model of agricultural demand, production and trade, IMPACT uses a system of food supply-and-demand equations to analyze baseline and alternative scenarios for global food demand, food supply, trade, income and population. Supply-and-demand functions incorporate supply-and-demand elasticities to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Country and regional agricultural sub-models are linked through trade. Within each country or regional sub-model, supply, demand and prices for agricultural commodities are determined.

The original IMPACT assumed 'normal' climate conditions, and therefore the impacts of annual weather variability on food production, demand and trade were not reflected. The inclusion of a water simulation module (WSM) enables IMPACT to reflect the effects of water demand and availability on food production and consumption, the interannual variability of water demand and availability, and the competition



Note: ISPAM (spatial distribution of crops based on crop calendars, soil characteristics and climate of 20 most important crops).

Figure 9.1 Model linkages between IMPACT and GTAP-W

for water among various economic sectors (Rosegrant et al., 2002). Within the model, WSM projects water demand for major water-use sectors and balances water availability as well as inter- and intra-sector water use by simulating seasonal storage regulation and water allocation for large river basins. In addition to variability, long-term trends in water availability and use for different sectors are projected, with exogenous drivers including population and income growth, changes in irrigated areas and improvements in water-use technology such as irrigation efficiency and new water sources (Rosegrant et al., 2002).

The model uses 281 ‘food-producing units’ (FPUs), which represent the spatial inter-sections of 115 economic world regions and 126 river basins (Figure 9.2 – see p. 253). Water simulation and crop production projections are conducted at the FPU level,

while projections of food demand and agricultural commodity trade are conducted at the country or economic region level. The disaggregation of spatial units improves the model's ability to represent the spatial heterogeneity of agricultural economies, and in particular, water resource availability and use.

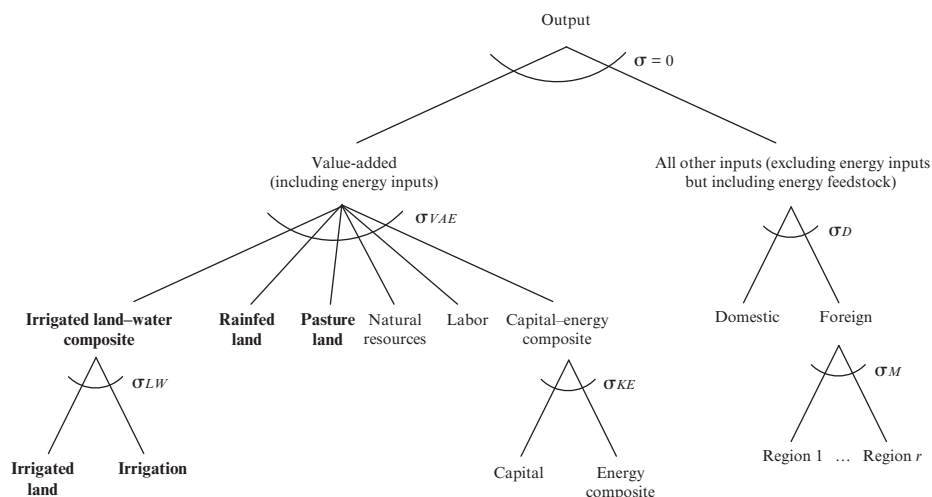
To analyze the impacts of global change, especially climate change, on regional and global food systems and to formulate appropriate adaptation measures, IMPACT was extended to include climate change components such as the yield effects of CO₂ fertilization and temperature changes, as well as altered hydrological cycles and changes in (irrigation) water demand and water availability through the development of a separate global hydrological model. This semi-distributed global hydrology model parameterizes the dominant hydrometeorological processes taking place at the land surface–atmosphere interface with a global scope. The model runs on a half-degree latitude–longitude grid, and uses global half-degree climate, soil and land surface cover data to determine a number of spatially distributed model parameters. The remaining parameters are determined through model calibration using global river discharge databases and data sets available elsewhere. For river basins for which data are not available for detailed calibration, regionalized model parameters are applied. The global hydrology model is able to convert the projections for future climate from global circulation models into hydrologic components such as evapotranspiration, runoff and soil moisture, which are used in this study (Zhu et al., 2008).

The GTAP-W Model

The GTAP-W model is a multiregional world CGE model. The model is a further refinement of the GTAP model¹ (Hertel, 1997) and is based on the version modified by Burniaux and Truong² (2002) as well as on the previous GTAP-W model introduced by Berrittella et al. (2007).

The new GTAP-W model is based on the GTAP version 6 database, which represents the global economy in 2001. The model has 16 world regions and 22 sectors, seven of which are in agriculture.³ However, the most significant change and principal characteristic of version 2 of the GTAP-W model is the new production structure, in which the original land endowment in the value-added nest has been split into pastureland and land for rainfed and for irrigated agriculture. Pastureland is basically the land used in the production of animals and animal products. The last two types of land differ as rainfall is free but irrigation development is costly. As a result, land equipped for irrigation is generally more valuable because yields per hectare are higher. To account for this difference we split irrigated agriculture further into the value of land and the value of irrigation. The value of irrigation includes the equipment but also the water necessary for agricultural production. In the short run the cost of irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability. The tree diagram in Figure 9.3 represents the new production structure.

Land as a factor of production in national accounts represents 'the ground, including the soil covering and any associated surface waters, over which ownership rights are enforced' (United Nations, 1993). To accomplish this we split, for each region and each crop, the value of land included in the GTAP social accounting matrix into the value of rainfed land and the value of irrigated land using its proportionate contribution to total



Note: The original land endowment has been split into pastureland, rainfed land, irrigated land and irrigation (in bold). σ is the elasticity of substitution between value-added and intermediate inputs, σ_{VAE} is the elasticity of substitution between primary factors, σ_{LW} is the elasticity of substitution between irrigated land and irrigation, σ_{KE} is the elasticity of substitution between capital and the energy composite, σ_D is the elasticity of substitution between domestic and imported inputs and σ_M is the elasticity of substitution between imported inputs.

Figure 9.3 Nested tree structure for industrial production process in GTAP-W (truncated)

production (Table 9.1).⁴ The value of pastureland is derived from the value of land in the livestock breeding sector. Regional information on rainfed and irrigated production by crop is based on IMPACT data (Rosegrant et al., 2002).

In the next step, we split the value of irrigated land into the value of land and the value of irrigation using the ratio of irrigated yield to rainfed yield. These ratios are based on IMPACT data (Table 9.2).⁵ The numbers indicate the relative value of irrigated agriculture compared to rainfed agriculture for particular land parcels. Irrigated and rainfed yields differ between crops as well as regions (not shown). For example, irrigation water is better applied to rice than to oilseeds on average. At the regional level, more crops are grown under irrigation in South America compared to North Africa or sub-Saharan Africa.

The procedure described above to introduce the four new endowments (pastureland, rainfed land, irrigated land and irrigation) allows us to avoid problems related to model calibration. In fact, since the original database is only split and not altered, the original regions' social accounting matrices are balanced and can be used by the GTAP-W model to assign values to the share parameters of the mathematical equations. Furthermore, the information supplied by IMPACT (demand and supply of water, demand and supply of food, rainfed and irrigated production and rainfed and irrigated area) provides detailed information for a robust calibration of a new baseline. For detailed information about the social accounting matrix (SAM) representation of the GTAP database, see McDonald et al. (2005).

Table 9.1 IMPACT 2000 base year data: share of irrigated production in total production by world region and crop (percentages)

Region*	Rice	Wheat	Cereal grains	Vegetables, fruits, nuts	Oilseeds	Sugar cane, sugar beet	Other agricultural products	Total
USA	51.01	78.93	70.25	34.20	68.45	48.00	100.00	67.73
CAN	0.00	1.92	10.36	34.72	3.33	44.08	0.00	8.50
WEU	48.77	19.56	16.28	35.32	5.69	40.28	5.03	24.10
JPk	93.71	79.66	65.26	66.26	32.10	56.64	81.50	75.48
ANZ	48.10	12.82	17.94	33.66	11.66	48.34	9.30	28.93
CEE	48.50	30.30	18.81	19.01	5.82	28.97	0.00	17.75
FSU	49.40	20.76	9.67	28.31	6.18	40.22	24.57	24.13
MDE	55.82	45.36	29.59	51.77	47.07	49.60	44.45	46.82
CAM	46.82	55.43	49.03	47.34	56.54	41.98	43.73	44.54
SAM	63.32	9.71	12.39	20.53	0.66	27.80	17.57	22.11
SAS	70.32	75.46	31.05	33.55	31.53	62.55	41.47	53.27
SEA	48.59	49.43	30.67	25.16	45.26	51.96	24.62	36.64
CHI	100.00	85.91	73.32	26.99	46.83	41.74	82.65	59.59
NAF	82.09	63.92	76.49	56.02	46.76	49.65	65.34	60.68
SSA	20.80	28.95	4.75	4.20	5.92	42.06	1.07	8.97
SIS	49.46	49.75	10.78	25.41	56.09	39.33	22.38	33.52
Total	73.16	48.42	42.30	28.13	37.06	43.97	47.53	42.16

Notes:

* For full names of regions, see Table 9.3.
2000 data are three-year averages for 1999–2001.

The GTAP-W model accounts only for water resources used in the agricultural sector, which consumes globally about 70 per cent of total freshwater resources. Domestic, industrial and environmental water uses are not considered by the model. Therefore the model does not account for alternative uses of water outside the agricultural sector, even though the value of water is generally much higher for domestic and industrial uses. The water industry in GTAP-W accounts only for the collection, purification and distribution of water to the industrial sector and provides no information on the amount of water used or its price.

As in all CGE models, the GTAP-W model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modelled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested constant elasticity of substitution (CES) functions (lower diagram Figure 9.3). Domestic and foreign inputs are not perfect substitutes according to the so-called ‘Armington assumption’, which accounts for product heterogeneity between world regions.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pastureland, rainfed land, irrigated land, irrigation, labor and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. Pastureland, rainfed land, irrigated land, irrigation and natural

Table 9.2 IMPACT 2000 base year data: ratio of irrigated yield to rainfed yield by world region and crop

Region*	Rice	Wheat	Cereal grains	Vegetables, fruits, nuts	Oilseeds	Sugar cane, sugar beet	Other agricultural products
USA	1.42	1.42	1.42	1.41	1.35	1.42	1.31 [†]
CAN	—	1.36	1.38	1.39	1.30	1.41	1.31 [†]
WEU	1.42	1.36	1.36	1.39	1.30	1.39	1.26
JPK	1.39	1.37	1.36	1.42	1.35	1.43	1.33
ANZ	1.41	1.39	1.38	1.39	1.32	1.43	1.33
CEE	1.41	1.37	1.36	1.36	1.32	1.38	1.31 [†]
FSU	1.42	1.38	1.38	1.40	1.33	1.40	1.32
MDE	1.33	1.36	1.36	1.38	1.37	1.36	1.29
CAM	1.43	1.41	1.40	1.40	1.33	1.39	1.30
SAM	1.44	1.54	1.36	1.36	1.33	1.47	1.30
SAS	1.43	1.41	1.38	1.40	1.39	1.41	1.32
SEA	1.42	1.40	1.35	1.36	1.34	1.41	1.31
CHI	1.40 [†]	1.42	1.42	1.38	1.40	1.44	1.32
NAF	1.33	1.37	1.33	1.34	1.33	1.34	1.31
SSA	1.37	1.36	1.34	1.36	1.34	1.34	1.32
SIS	1.39	1.41	1.34	1.34	1.33	1.39	1.31

Notes:

* For full names of regions, see Table 9.3.

† World average.

2000 data are three-year averages for 1999–2001.

resources are imperfectly mobile across agricultural sectors. While perfectly mobile factors earn the same market return regardless of where they are employed, market returns for imperfectly mobile factors may differ across sectors. The national income is allocated between aggregate household consumption, public consumption and savings. Constant budget shares are devoted to each category via a Cobb–Douglas utility function assumption. Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the constant difference in elasticities (CDE) form: a non-homothetic function that is used to account for possible differences in income elasticities for the various consumption goods. A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.

In the GTAP model and its variants, two industries are unrelated to any region. International transport is a world industry that produces the transportation services associated with the movement of goods between origin and destination regions. Transport services are produced by means of factors submitted by all regions, in variable proportions. In a similar way, a hypothetical global bank collects savings from all regions and allocates investments so as to achieve equality of expected rates of return (macroeconomic closure).

In the original GTAP model, land is combined with natural resources, labor and the capital–energy composite in a value-added nest. In our modeling framework we

incorporate the possibility of substitution between land and irrigation in irrigated agricultural production by using a nested CES function (lower diagram Figure 9.3). The procedure for obtaining the elasticity of factor substitution between land and irrigation (σ_{LW}) is explained in more detail in Appendix B.⁶ Next, the irrigated land–water composite is combined with pasture land, rainfed land, natural resources, labor and the capital–energy composite in a value-added nest through a CES structure. The original elasticity of substitution between primary factors (σ_{VAE}) is used for the new set of endowments.

In the benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of water used for irrigated agriculture in IMPACT. An initial sector- and region-specific shadow price for irrigation water can be obtained by combining the SAM information about payments to factors and the volume of water used in irrigation from IMPACT.

THE IMPACT OF CLIMATE CHANGE

Climate Change Simulation

In our analysis, we use the B2 (intermediate growth) scenario, a rather moderate scenario from the *Special Report on Emissions Scenario* (SRES) (IPCC, 2000), as the climate change projections out to 2050.⁷ The effects of temperature and CO₂ fertilization on crop yields are based on the IMAGE model (Bouwman et al., 2006). Recent research findings show that the stimulation of crop yield observed in the global free air carbon enrichment (FACE) experiments fell well below (about half) the value predicted from chambers (Long et al., 2006). Consequently, compared to chamber results, model projections of future yields should probably use much lower CO₂ fertilization factors. In addition, when nitrogen is limiting, as is the case in much of sub-Saharan Africa, the CO₂ fertilization effect is dramatically reduced. So the actual benefits in farmer fields of CO₂ fertilization remain uncertain. Therefore we apply 50 per cent of the CO₂ fertilization factors from the IMAGE model simulation in IMPACT (Rosegrant et al., 2009).

In addition to the effects of higher CO₂ concentration levels and changes in temperature, climate change is likely to affect the volume and the spatial and temporal distribution of rainfall and runoff, which in turn affect the number and distribution of people under water stress and the productivity of world agricultural systems. We use climate inputs from the Hadley Centre Coupled Model (HadCM3) run of the B2 scenario that was statistically downscaled to a 0.5 degree latitude–longitude global grid using the pattern scaling method of the Climate Research Unit at the University of East Anglia (Mitchell et al., 2004). The semi-distributed macro-scale hydrology module of IMPACT derives effective precipitation, potential and actual evapotranspiration, as well as runoff at these 0.5 degree pixels and scales them up to each of the 281 FPUs, the spatial operational units of IMPACT. Projections for water requirements, infrastructure capacity expansion and improvement in water-use efficiency are also conducted by IMPACT. These projections are combined with the simulated hydrology model to estimate water use and consumption.

To explore food security effects, the model projects the percentage and number of

malnourished preschool children (0–5 years old) in developing countries. A malnourished child is a child whose weight for age is more than two standard deviations below the median reference standard set by the US National Center for Health Statistics and the World Health Organization. The number of malnourished preschool children in developing countries is projected as a function of per capita calorie availability, the ratio of female to male life expectancy at birth, total female enrollment in secondary education as a percentage of the female age-group corresponding to national regulations for secondary education, and the percentage of population with access to safe water. These variables were found to be key determinants of childhood malnutrition in the meta-analysis of Smith and Haddad (2000).

In the next section the results of the *IMPACT climate change simulation* out to 2050 are compared to an alternative *no climate change simulation* assuming current climate conditions. The GTAP-W model uses these outputs from IMPACT to calibrate a hypothetical general equilibrium in 2050 for each of these two simulations.

To obtain a 2050 benchmark equilibrium data set for the GTAP-W model, we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future by imposing forecasted values for some key economic variables in the initial calibration data set. That is, we impose a forecast closure exogenizing macroeconomic variables for which forecasts are available. In this way, we impose forecasted changes in regional endowments (labor, capital, natural resources, rainfed land, irrigated land and irrigation), in regional factor-specific and multi-factor productivity and in regional population. We use estimates of regional labor productivity, labor stock, and capital stock from the G-Cubed model (McKibbin and Wilcoxon, 1998). Changes in the allocation of rainfed and irrigated land within a world region, as well as irrigation and agricultural land productivity, are implemented according to the values obtained from IMPACT. Finally, we use the medium-variant population estimates for 2050 from the Population Division of the United Nations (United Nations, 2004).

The link of the two models allows for improved calibration and enhanced insights into policy impacts. In fact, the information supplied by the IMPACT model (demand and supply of water, demand and supply of food, rainfed and irrigated production, and rainfed and irrigated area) provides the GTAP-W model with detailed information for a robust calibration of a new data set and allows us to run climate change scenarios.

Climate Change Simulation Results

As can be seen in Tables 9.3 and 9.4, expansion of area harvested will contribute little to future food production growth under historic climate conditions. In China, for example, area is expected to contract at 0.2 per cent per year. An exception is sub-Saharan Africa, where crop area is still expected to increase at 0.6 per cent annually. The projected slowdown in crop area expansion places the burden to meet future food demand on crop yield growth. However, although yield growth will vary considerably by commodity and country, in the aggregate and in most countries it also will continue to slow down. The global yield growth rate for all cereals is expected to decline from 2.0 per cent per year in 1980–2000 to 1.0 per cent per year in 2000–2050. By 2050, approximately one third of crop harvested area is projected to be under irrigation. In sub-Saharan Africa, irrigated

Table 9.3 IMPACT 2000 base year data: crop harvested area and production by world region and for sub-Saharan Africa

Regions	Description	Rainfed agriculture		Irrigated agriculture		Total agriculture		Share of irrigated agriculture in total	
		Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (%)	Production (%)
USA		38 471	211 724	69 470	442 531	107 942	654 255	64.4	67.6
Canada		27 267	65 253	717	6065	27 984	71 318	2.6	8.5
Western Europe		59 557	462 403	10 164	146 814	69 721	609 217	14.6	24.1
Japan and South Korea		1 553	23 080	4 909	71 056	6 462	94 136	76.0	75.5
Australia and New Zealand		21 500	67 641	2 387	27 656	23 886	95 297	10.0	29.0
Eastern Europe		38 269	187 731	6 091	40 638	44 360	228 369	13.7	17.8
Former Soviet Union		86 697	235 550	18 443	75 798	105 139	311 347	17.5	24.3
Middle East		30 553	135 872	21 940	119 626	52 493	255 498	41.8	46.8
Central America		13 030	111 665	8 794	89 698	21 824	201 364	40.3	44.5
South America		80 676	650 313	10 138	184 445	90 814	834 758	11.2	22.1
South Asia		143 427	492 718	120 707	563 161	264 134	1 055 879	45.7	53.3
Southeast Asia		69 413	331 755	27 464	191 890	96 876	523 645	28.3	36.6
China		66 715	617 460	124 731	909 561	191 446	1 527 021	65.2	59.6
North Africa		15 714	51 163	7 492	78 944	23 206	130 107	32.3	60.7
Sub-Saharan Africa		175 375	440 800	6 243	43 398	181 618	484 199	3.4	9.0
Rest of the World		3 813	47 467	1 094	23 931	4 906	71 398	22.3	33.5
Total		872 029	4 132 597	440 782	3 015 211	1 312 811	7 147 808	33.6	42.2
Sub-Saharan African crops									
1	Rice	6015	6 117	965	1 606	6 979	7 723	13.8	20.8
2	Wheat	2 043	3 288	422	1 340	2 465	4 628	17.1	28.9
3	Cereal grains	65 723	65 912	2 394	3 286	68 117	69 197	3.5	4.7
4	Vegetables, fruits, nuts	31 570	224 570	1 111	9 846	32 681	234 415	3.4	4.2
5	Oilseeds	9 969	8 804	551	554	10 520	9 358	5.2	5.9
6	Sugarcane, sugar beet	822	35 280	309	25 614	1 131	60 894	27.3	42.1
7	Other agricultural products	59 235	96 830	490	1 153	59 725	97 983	0.8	1.2
Total		175 375	440 800	6 243	43 398	181 618	484 199	3.4	9.0

Note: 2000 data are three-year averages for 1999-2001.

harvested area is projected to grow more than twice as fast as rainfed area (79 per cent compared to 34 per cent). However, the proportion of irrigated area to total area in 2050 is only 1.1 per cent higher compared to 2000 (4.5 and 3.4 per cent, respectively).

Impacts of future climate change on food production, demand and trade are reflected in the 2050 (SRES B2) climate change simulation. Table 9.5 reports the percentage change in crop harvested area and production by world region, and by crop for sub-Saharan Africa as well as changes in regional GDP and welfare between the 2050 no climate change simulation and the 2050 (SRES B2) climate change simulation. According to the analysis, the world's crop harvested area and food production decrease by 0.3 and 2.7 per cent, respectively. The picture is similar for irrigated production: both area and production are projected to be lower, by 1.5 and 4.0 per cent, respectively. Global rainfed production decreases by 1.6 per cent despite an increase in rainfed area of about 0.4 per cent. The regional impacts of climate change on rainfed, irrigated and total crop production vary widely. In sub-Saharan Africa, both rainfed and irrigated harvested areas decrease when climate change is considered (by 0.6 and 3.5 per cent, respectively). Rainfed production, in contrast, increases by 0.7 per cent, while irrigated production drops sharply by 15.3 per cent, as some of the irrigated crops such as wheat are more susceptible to heat stress, and runoff available to irrigation declines significantly in some African basins. As a result, total crop harvested area and production in sub-Saharan Africa decrease by 0.7 per cent and 1.5 per cent, respectively. Most of the decline in production can be attributed to wheat (24.1 per cent) and sugarcane (10.6 per cent). As a result, irrigated wheat might not be significant in the food production systems of sub-Saharan Africa. Other crops in sub-Saharan Africa actually do better because of climate change, particularly under CO₂ fertilization.

The last three columns in Table 9.5 show the impact of climate change on regional GDP and welfare. At the global level, GDP is expected to decrease due to climate change by US\$87 billion, equivalent to 0.1 per cent of global GDP. At the regional level, only Australia and New Zealand experience a positive GDP impact under climate change: GDP is expected to increase by US\$1.1 billion. Projected declines in GDP are particularly high for the USA, South Asia and South America (US\$19.8 billion, US\$17.3 billion and US\$10.7 billion, respectively). In relative terms, declines are largest for South Asia, the former Soviet Union and Eastern Europe (0.6, 0.6 and 0.4 per cent, respectively). For sub-Saharan Africa, losses in GDP due to climate change are estimated at US\$3.3 billion, equivalent to 0.2 per cent of regional GDP. Alternatively, when yield effects of CO₂ fertilization are not considered, GDP losses in sub-Saharan Africa are estimated to be slightly higher (US\$4.5 billion).

Like global GDP, global welfare is expected to decline due to climate change. However, welfare changes due to declines in agricultural productivity and crop harvested area are not uniform; in some world regions welfare increases as their relative competitive position improves with respect to other regions. This is the case for South America, Australia and New Zealand, sub-Saharan Africa and Canada. Projected welfare losses are considerable for South Asia, the USA and Western Europe. The US\$2 billion welfare increase in sub-Saharan Africa is explained as follows. First, only some crops in sub-Saharan Africa are badly hit by climate change under this very moderate scenario. Second, crops in other parts of the world are also adversely affected to a greater extent than those in sub-Saharan Africa, partially as a result of higher fertilizer use. Nelson et al. (2009) and

Table 9.4 2050 no climate change simulation: crop harvested area and production by world region and for sub-Saharan Africa
(results from IMPACT)

Regions	Description	Rainfed agriculture		Irrigated agriculture		Total agriculture		Share of irrigated agriculture in total	
		Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (%)	Production (%)
USA		34 549	363 602	71 736	877 262	106 285	1 240 864	67.5	70.7
Canada		21 827	97 335	620	9 640	22 447	106 975	2.8	9.0
Western Europe		39 852	452 311	8 310	188 656	48 162	640 967	17.3	29.4
Japan and South Korea		1 107	27 348	3 770	72 337	4 876	99 685	77.3	72.6
Australia and New Zealand		20 143	109 878	2 281	49 614	22 424	159 492	10.2	31.1
Eastern Europe		29 491	232 568	4 983	70 048	34 474	302 616	14.5	23.1
Former Soviet Union		81 142	413 531	18 703	144 623	99 845	558 154	18.7	25.9
Middle East		31 498	212 401	24 624	280 975	56 122	493 376	43.9	56.9
Central America		13 501	259 872	10 425	221 510	23 926	481 382	43.6	46.0
South America		101 888	2 232 862	13 842	675 526	115 729	2 908 388	12.0	23.2
South Asia		101 386	646 745	152 776	1 293 716	254 161	1 940 461	60.1	66.7
Southeast Asia		77 618	602 683	27 764	451 772	105 382	1 054 454	26.3	42.8
China		61 100	813 928	120 562	1 191 019	181 662	2 004 948	66.4	59.4
North Africa		16 849	114 127	8 426	159 367	25 274	273 494	33.3	58.3
Sub-Saharan Africa		235 169	1 074 930	11 194	175 561	246 363	1 250 491	4.5	14.0
Rest of the World		4 439	117 191	1 428	78 063	5 867	195 254	24.3	40.0
Total		871 559	7 771 313	481 443	5 939 688	1 353 002	13 711 001	35.6	43.3
Sub-Saharan African crops									
1 Rice		6 068	11 829	2 362	9 893	8 430	21 722	28.0	45.5
2 Wheat		2 885	12 576	574	3 589	3 458	16 165	16.6	22.2
3 Cereal grains		83 488	180 022	3 505	12 972	86 994	192 994	4.0	6.7
4 Vegetables, fruits, nuts		40 634	535 837	2 213	40 862	42 846	576 700	5.2	7.1
5 Oilseeds		13 456	15 782	655	1 115	14 110	16 897	4.6	6.6
6 Sugarcane, sugar beet		1 661	11 7818	727	101 199	2 388	219 016	30.4	46.2
7 Other agricultural products		86 978	201 066	1 159	5 930	88 136	206 997	1.3	2.9
Total		235 169	1 074 930	11 194	175 561	246 363	1 250 491	4.5	14.0

Table 9.5 Impact of climate change in 2050: percentage change in crop harvested area and production by world region and for sub-Saharan Africa as well as change in regional GDP (results from IMPACT)

Regions	Description	Rainfed agriculture		Irrigated agriculture		Total agriculture		Change in GDP*		Change in welfare* US\$ million
		Area	Production	Area	Production	Area	Production	Percentage	US\$ million	
USA		1.56	-1.68	-3.26	-7.18	-1.70	-5.57	-0.07	-19768	-17076
Canada		2.02	-2.99	3.32	7.67	2.05	-2.03	-0.05	-992	1737
Western Europe		1.21	-0.18	1.64	0.10	1.28	-0.10	-0.01	-1942	-12612
Japan and South Korea		-0.74	0.26	0.02	1.20	-0.15	0.94	0.00	-582	-2190
Australia and New Zealand		2.24	3.16	2.64	1.05	2.28	2.51	0.09	1074	5784
Eastern Europe		1.20	-1.73	2.18	-1.21	1.34	-1.61	-0.38	-5201	-9537
Former Soviet Union		1.55	-4.16	0.51	2.97	1.36	-2.31	-0.58	-8734	-12039
Middle East		0.44	-3.85	-9.02	-9.76	-3.71	-7.22	-0.23	-6724	-8853
Central America		0.98	-8.59	-0.01	-3.13	0.55	-6.08	-0.21	-5133	-914
South America		0.22	-3.43	-2.42	-8.42	-0.10	-4.59	-0.21	-10697	6055
South Asia		0.20	1.71	1.47	-2.06	0.96	-0.80	-0.64	-17271	-24573
Southeast Asia		0.19	-0.28	-0.70	-1.94	-0.04	-0.99	-0.12	-4073	-9644
China		0.37	-0.38	-3.61	-1.65	-2.27	-1.14	-0.01	-677	-2710
North Africa		0.66	-3.42	-2.87	-1.78	-0.52	-2.47	-0.14	-1146	-108
Sub-Saharan Africa		-0.59	0.70	-3.51	-15.30	-0.72	-1.55	-0.20	-3333	1786
Rest of the World		0.60	-2.85	-2.87	-4.86	-0.25	-3.65	-0.22	-1716	-2111
Total		0.38	-1.65	-1.55	-3.99	-0.30	-2.66	-0.09	-86914	-87004
Sub-Saharan African crops										
1 Rice		-1.95	0.88	-2.50	5.44	-2.10	2.96			
2 Wheat		2.14	-24.86	-7.86	-21.47	0.48	-24.11			
3 Cereal grains		0.63	1.26	-1.24	-1.63	0.55	1.07			
4 Vegetables, fruits, nuts		-0.34	1.14	-1.53	-1.93	-0.41	0.92			
5 Oilseeds		-1.16	0.33	-0.67	1.68	-1.14	0.42			
6 Sugarcane, sugar beet		1.27	2.11	-23.85	-25.35	-6.37	-10.58			
7 Other agricultural products		-1.81	-0.19	-2.95	0.16	-1.83	-0.18			
Total		-0.59	0.70	-3.51	-15.30	-0.72	-1.55			

Notes:

Change with respect to the 2050 no climate change simulation.

* Results from GTAP-W.

ADB (2009) also find that climate change impacts, in terms of yield declines, are largest in Asia and relatively lower in sub-Saharan Africa. The overall result is an increase in food prices and exports. Higher exports improve welfare (as measured by the Hicksian Equivalent Variation). Higher food prices in turn result in reduced affordability and accessibility of food for the poorest, and also dampen food demand. As a consequence, malnutrition levels increase by around 2 million children.

The losses in GDP due to climate change are used below to evaluate the efficacy of two adaptation scenarios to cope with climate change in sub-Saharan Africa. Many studies underline that the human response is crucially important. In fact, adaptation may alleviate any negative impact caused by climate change, whereas maladaptation may exacerbate the situation.

AGRICULTURE IN SUB-SAHARAN AFRICA

Agriculture is of great importance to most sub-Saharan African economies, supporting between 70 and 80 per cent of employment and contributing an average of 30 per cent of gross domestic product (GDP) and at least 40 per cent of exports (Commission for Africa, 2005). However, specific agro-ecological features, small farm sizes, poor access to services and knowledge, and low investment in infrastructure and irrigation schemes have limited agricultural development in sub-Saharan Africa (Faurès and Santini, 2008).

Rainfed farming dominates agricultural production in sub-Saharan Africa, covering around 97 per cent of total cropland, and exposes agricultural production to high seasonal variability in rainfall. Although irrigation systems have been promoted in the region, the impact has not been as expected. Reasons include a lack of demand for irrigated products, poor market access, low incentives for agricultural intensification, unfavorable topography, low-quality soils and inadequate policy environments (Burke et al., 2006; Faurès and Santini, 2008). Although the cost of irrigation projects implemented in developing countries has generally decreased over the last four decades and performance of irrigation projects has improved (Inocencio et al., 2007), the situation in sub-Saharan Africa is different. This world region has higher costs on average than other regions.

Agriculture in sub-Saharan Africa is characterized by comparably low yields. While Asia experienced a rapid increase in food production and yields during the Green Revolution in the 1970s and early 1980s, in sub-Saharan Africa per capita food production and yields have stagnated. The failure of agriculture to take off in sub-Saharan Africa has been attributed to the dependence on rainfed agriculture; low population densities; the lack of infrastructure, markets and supporting institutions; the agro-ecological complexities and heterogeneity of the region; low use of fertilizers; and degraded soils (Johnson et al., 2003; World Bank, 2007).

Future climate change may present an additional challenge for agriculture in sub-Saharan Africa. According to the Intergovernmental Panel on Climate Change (IPCC) (Watson et al., 1997), Africa is the most vulnerable region to climate change because widespread poverty limits adaptive capacity. The impacts of climate change on agriculture could seriously worsen livelihood conditions for the rural poor and increase food insecurity in the region. Smallholders and pastoralists in sub-Saharan Africa will need

to gradually adapt and adopt technologies that increase the productivity, stability and resilience of production systems (Faurès and Santini, 2008).

STRATEGIES FOR ADAPTATION TO CLIMATE CHANGE IN SUB-SAHARAN AFRICA

The *World Development Report 2008* (World Bank, 2007) suggests that the key policy challenge in agriculture-based economies such as those in sub-Saharan Africa is to help agriculture play its role as an engine of growth and poverty reduction. Development of irrigation and improvements in agricultural productivity have proven to be effective in this regard. Hussain and Hanjra (2004) identify three main pathways through which irrigation can impact poverty. Irrigation in the micro-pathway increases returns to the physical, human and social capital of poor households, and enables smallholders to achieve higher yields and revenues from crop production. The meso-pathway includes new employment opportunities on irrigated farms or higher wages on rainfed farms. Lower food prices are also expected, as irrigation enables farmers to obtain more output per unit of input. In the macro-pathway, or growth path, gains in agricultural productivity through irrigation can stimulate national and international markets, improving economic growth and creating second-generation positive externalities.

Faurès and Santini (2008) suggest that improvements in agricultural productivity can provide a pathway out of poverty for rural households in several ways. Poor households that own land benefit from improvements in crop and livestock yields through greater output and higher incomes. Households that do not own land but provide farm labor benefit from higher demand for farm labor and wages. Households that do not own land or that provide farm labor benefit from a greater supply of agricultural products and lower food prices. Improvements in agricultural productivity can also benefit non-agricultural rural households and urban households through greater demand for food and other products (stimulated by higher agricultural incomes and higher net incomes in non-agricultural households). Food processing and marketing activities can also be promoted in urban areas. When agricultural productivity improves by means of water management, the incremental productivity of complementary inputs raises and expands the demand for these inputs, which in turn stimulates non-agricultural economic activities.

However, the effectiveness of irrigation and agricultural productivity in reducing poverty and promoting economic growth is affected by the availability of affordable complementary inputs, the development of human capital, access to markets and expansion of markets to achieve economies of scale, and institutional arrangements that promote farm-level investments in land and water resources (CA, 2007; Faurès and Santini, 2008).

Sub-Saharan Africa has the potential for expanding irrigation and increasing agricultural productivity. The *World Development Report 2008* (World Bank, 2007) points out that the new generation of better-designed irrigation projects and the large untapped water resources generate opportunities to invest in irrigation in sub-Saharan Africa. New investments in irrigation need complementary investments in roads, extension services and access to markets. The Comprehensive Assessment of Water Management in Agriculture (CA, 2007) suggests that where yields are already high and the exploitable

gap is small, projected growth rates are low, whereas low yields present a large potential for improvement. In sub-Saharan Africa, observed yields are less than one-third of the maximum attainable yields. The potential for productivity enhancement is therefore large, particularly for maize, sorghum and millet. Although water is often the principal constraint for agricultural productivity, optimal access to complementary inputs and investment in R&D are also necessary.

As discussed above, the development of irrigation and improvements in agricultural productivity are key variables, not only for future economic development, poverty reduction and food security in sub-Saharan Africa, but also for climate change adaptation. In this sense, we evaluate the economy-wide impacts on production and income of expanding irrigation and increasing agricultural productivity in sub-Saharan Africa. Both adaptation scenarios are implemented based on the 2050 (SRES B2) climate change simulation using both a partial equilibrium model (IMPACT) and a general equilibrium model (GTAP-W). The first adaptation scenario assumes an expansion in the capacity of irrigated agriculture and doubles the irrigated area in sub-Saharan Africa. The second adaptation scenario considers improvements in productivity for both rainfed and irrigated agriculture – increasing rainfed and irrigated yields in sub-Saharan Africa by 25 per cent through investments in agricultural R&D and enhanced farm management practices.

According to the first adaptation scenario, irrigated areas in sub-Saharan Africa are assumed to double by 2050, as compared to the 2050 (SRES B2) climate change simulation, while total cropland does not change. Around 11 million hectares are thus transferred from rainfed agriculture to irrigated agriculture, increasing irrigated areas in the region from a very small base to nearly 9 per cent of the total crop area in the region. In GTAP-W, the initial irrigated land and irrigation endowments are doubled; the rainfed land endowment is reduced accordingly. In IMPACT, for each FPU and each crop, irrigated area growth is doubled for the region. Rainfed area is reduced by an equal amount to keep total crop area constant. Other growth assumptions remain unchanged.

In the second adaptation scenario, agricultural crop productivity for both rainfed and irrigated crops in sub-Saharan Africa is increased by 25 per cent compared to the 2050 (SRES B2) climate change simulation. In GTAP-W, the primary factor productivity of rainfed land, irrigated land and irrigation is increased by 25 per cent. In IMPACT, crop-yield growth rates are increased to reach values 25 per cent above baseline values.

To account for the level of investment costs required for each scenario, we use estimates from IMPACT. The most important investment drivers in IMPACT are irrigation, rural roads, education, clean water provision and agricultural research (for more detail on methodology see Rosegrant et al., 2001). The estimates represent the investment effort required for doubling irrigated areas and increasing agricultural yields in sub-Saharan Africa. A total of US\$2.8 billion per year would be required to double irrigated areas in sub-Saharan Africa over the 2010–50 timeframe. Direct investments in irrigation account for 86 per cent of total investment, the remainder being for associated rural road expansion. Investment costs required to improve agricultural yields by 25 per cent in sub-Saharan Africa are slightly lower, at US\$2.7 billion per year. While costs of increased investment in agricultural research account for 12 per cent, costs related to market access and road expansion represent 88 per cent. As investments in sub-Saharan Africa trigger

global changes in area, yield and food prices, investment needs also increase slightly in other regions but decline elsewhere.

Table 9.6 presents for the 2050 (SRES B2) climate change simulation crop harvested area and production in sub-Saharan Africa by crop. Only 4.4 per cent of the total crop harvested area is expected to be under irrigation by 2050, while irrigated production is expected to account for 12.1 per cent of the total agricultural production in the region. The two major irrigated crops are rice and sugarcane. Irrigated rice is expected to account for more than one-fourth of the total rice harvested area, and to contribute almost half of the total rice production. The picture is similar for irrigated sugarcane. Almost one-fourth of the total crop area is projected to be under irrigation, and around 38.6 per cent of the total crop production is expected to be irrigated. Most of the total crop area under irrigation is devoted to the production of cereal grains, rice, vegetables, fruits and nuts. However, with the exception of rice, the share of irrigated harvested area as a percentage of total crop harvested area is projected to be less than 5.1 per cent. Similarly, almost 80 per cent of the total rainfed harvested area in sub-Saharan Africa is projected to be used for the production of cereals, roots and tubers, vegetables, groundnuts and fruits.

Adaptation Scenario 1: Expansion of Irrigated Agriculture

In the original GTAP model, land is specific to the agricultural sector, but not to individual crops that compete for land. In the GTAP-W model this proposition also holds. Rainfed land, irrigated land and irrigation are sector-specific, but individual crops compete for them. Pastureland is only used by the livestock sector. Therefore, when the capacity of irrigated agriculture is increased by transferring land from rainfed agriculture to irrigated agriculture, the additional land in irrigated agriculture is not allocated uniformly. Irrigated wheat production uses a higher proportion of the new land and irrigation than other crops (Table 9.7), an outcome that is mostly driven by a strong regional consumption of locally produced wheat. Similarly the reduction in rainfed land is not proportional among crops. While the use of rainfed land decreases between 0.04 and 0.5 per cent for most crops, the use of rainfed land for wheat production increases by 1.3 per cent. The combined effect is an increase in total wheat production of 2.1 per cent, which is consistent with an increase in irrigated and rainfed production of 102.2 and 0.5 per cent, respectively. The change in production of oilseeds shows a similar picture: irrigated and rainfed production increase by 100.1 and 0.03 per cent, respectively. For the rest of the crops, irrigated production increases and rainfed production decreases, resulting in an increase in total crop production. The only exception is the 'other agricultural products' sector, for which total production decreases by 0.05 per cent.

The expansion of irrigated areas in the region from a very small base helps farmers achieve higher yields per hectare. This is followed by an increase in total crop production and a drop in agricultural commodity prices. The last two columns in Table 9.7 show a reduction in domestic and global market prices for all crops (an exception is the increase in the domestic price of other agricultural products). As a result, the number of malnourished children is expected to decline by around 0.3 million children (Figure 9.4).

As a general equilibrium model, GTAP-W accounts for impacts in the non-agricultural sectors as well. Changes in total crop production have a mixed effect on non-agricultural sectors; the domestic and world prices of non-agricultural products increase under this

Table 9.6 2050 climate change simulation: crop harvested area and production in sub-Saharan Africa (results from IMPACT)

Agricultural products (according to GTAP-W)	Rainfed agriculture		Irrigated agriculture		Total agriculture		Share of irrigated agriculture in total	
	Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (thousand ha)	Production (thousand mt)	Area (%)	Production (%)
1 Rice	5950	11933	2303	10432	8253	22364	27.9	46.6
2 Wheat	2946	9450	529	2818	3475	12268	15.2	23.0
3 Cereal grains	84012	182298	3462	12761	87474	195058	4.0	6.5
4 Vegetables, fruits, nuts	40493	541953	2179	40072	42673	582025	5.1	6.9
5 Oilseeds	13300	15834	650	1134	13950	16968	4.7	6.7
6 Sugarcane, sugar beet	1683	120306	553	75545	2236	195851	24.8	38.6
7 Other agricultural products	85400	200684	1125	5939	86525	206623	1.3	2.9
Total	233784	1082457	10801	148701	244585	1231158	4.4	12.1

Table 9.7 Expansion of irrigated agriculture: percentage change in the demand for endowments, total production and market price in sub-Saharan Africa (results from GTAP-W)

GTAP-W sectors	Change in demand for endowments (%)						Change in production (%)			Change in market price (%)	Change in world market price (%)*		
	Irriga- tion	Irrigated land	Rainfed land	Pasture- land	Unskilled labor	Skilled labor	Capital	Natural resources	Irrigated			Rainfed	Total
1 Rice	99.57	99.60	-0.18		-0.17	-0.17	-0.17		99.59	-2.57	0.16	-1.12	-0.06
2 Wheat	102.63	102.66	1.35		1.73	1.73	1.73		102.24	0.49	2.12	-1.17	-0.05
3 Cereal grains	99.85	99.87	-0.04		0.00	0.00	0.00		99.87	-0.47	0.05	-0.14	-0.02
4 Vegetable, fruits, nuts	99.94	99.96	0.00		0.06	0.05	0.05		98.06	0.00	0.09	-0.10	-0.01
5 Oilseeds	100.14	100.17	0.11		0.18	0.18	0.18		100.12	0.03	0.24	-0.18	-0.02
6 Sugarcane, sugar beet	98.87	98.89	-0.53		-0.61	-0.61	-0.61		98.88	-7.32	0.17	-1.87	-0.17
7 Other agricultural products	99.76	99.78	-0.09		-0.05	-0.05	-0.06		99.78	-0.17	-0.05	0.01	-0.01
8 Animals				0	0.02	0.02	0.02				0.00	0.07	0.01
9 Meat					-0.06	-0.06	-0.06				-0.06	0.05	0.00
10 Food products					0.11	0.11	0.11				0.11	-0.17	-0.01
11 Forestry					0.00	0.00	0.00	0.00			0.00	0.02	0.00
12 Fishing					0.04	0.04	0.04	0.00			0.02	0.12	0.01
13 Coal					-0.01	-0.01	-0.01	0.00			-0.01	0.01	0.00
14 Oil					-0.02	-0.02	-0.02	0.00			-0.02	0.01	0.00
15 Gas					-0.04	-0.04	-0.04	0.00			-0.03	0.01	0.00
16 Oil products					-0.01	-0.01	0.01				0.01	0.01	0.00
17 Electricity					-0.01	-0.01	-0.01				-0.01	0.02	0.00
18 Water					0.01	0.01	0.01				0.01	0.02	0.00
19 Energy-intensive industries					-0.03	-0.03	-0.03	0.00			-0.03	0.01	0.00
20 Other industries and services					-0.02	-0.02	-0.02				-0.02	0.01	0.00
21 Market services					0.00	0.00	0.00				0.00	0.01	0.00
22 Nonmarket services					0.00	0.00	0.00				0.00	0.01	0.00
Change in market price (%)	-90.57	-90.63	0.19	0.09	0.02	0.02	0.02	0.08					

Notes:

Percentage change with respect to the 2050 climate change simulation.

* World price index for total supply.

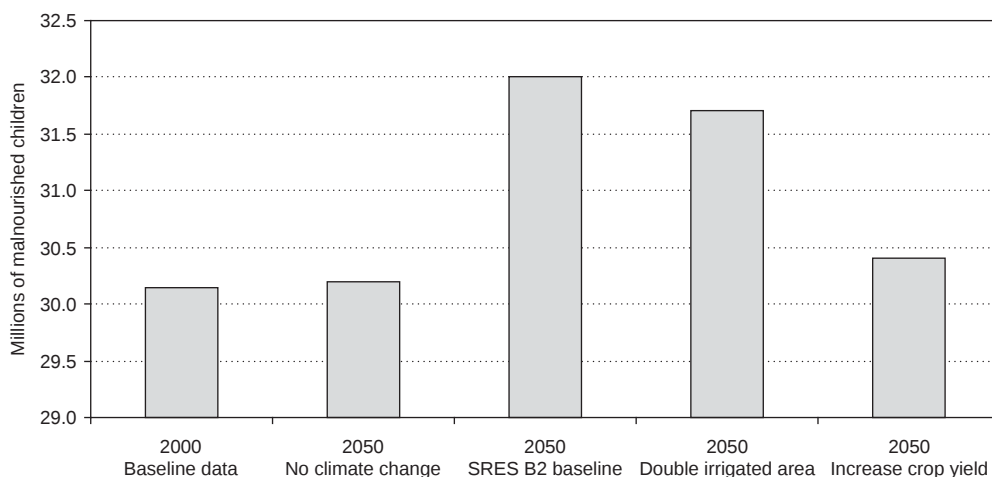


Figure 9.4 Number of malnourished children (<5 yrs) in sub-Saharan Africa, 2000 base year data and projected 2050 climate change simulations and alternative adaptation scenarios (million children) (results from IMPACT)

alternative scenario. An exception is the food products sector, in which prices decline because production is promoted by a higher supply and lower price of crops.

Factor market prices change according to the new factor composition. The increase in the supply of irrigated land and irrigation pushes down their market prices, while prices for rainfed land, as it becomes scarcer, experience a relative increase. Market prices for the rest of the primary factors increase as the economy expands (Table 9.7). Regional welfare increases by only about US\$119 million. Real absorption, defined as the change in government and private consumption and investment, increases even less to just around US\$45 million. This adaptation scenario leads to a small increase in GDP in sub-Saharan Africa (0.007 per cent, equivalent to US\$113 million), which is insufficient to compensate for the regional GDP losses expected under climate change (US\$3.3 billion) or for the annualized investment costs required for doubling irrigated areas (US\$2.8 billion).

Results from IMPACT are shown in Table 9.8. The expansion of irrigated areas in sub-Saharan Africa increases cereal production in the region by 5 per cent, and meat production by 1 per cent. No change can be seen for root and tuber production. The results are not readily comparable to those obtained by the GTAP-W due to the differences in aggregation. Contrary to the IMPACT results, meat production in the GTAP-W decreases slightly, by 0.06 per cent.

For all cereals, real commodity prices by 2050 under the (SRES B2) climate change simulation are expected to be higher than prices in 2000. This is a result of increased resource scarcity for both land and water, as well as the impact of climate change, biofuel development, increased population and income-growth-driven food demand diversification, with demand shifting toward meat, egg and milk products that require grain as feedstock. Climate change leads to higher mean temperatures and generally raises crop water requirements, but at the same time the availability of water for crop growth

Table 9.8 Expansion of irrigated agriculture: regional production and world market prices for cereals and meats, 2000 base year data and 2050 climate change simulations (results from IMPACT)

Description	2000 base year data	2050		Percentage change*
		Climate change simulation	Double irrigated area	
Cereal production (mmt):				
North America and Europe	779	1 188	1 196	0.67
Central West Asia and North Africa	116	240	233	-2.80
East and South Asia and Pacific	745	1 010	1 009	-0.06
Latin America and Caribbean	133	262	263	0.57
Sub-Saharan Africa	78	211	222	5.34
Root and tuber production (mmt):				
North America and Europe	171	198	198	0.36
Central West Asia and North Africa	21	48	46	-2.56
East and South Asia and Pacific	281	371	371	-0.05
Latin America and Caribbean	51	107	108	1.17
Sub-Saharan Africa	164	379	379	0.00
Meat production (mmt):				
North America and Europe	93	122	122	0.04
Central West Asia and North Africa	11	33	33	0.90
East and South Asia and Pacific	88	202	203	0.56
Latin America and Caribbean	30	82	83	1.13
Sub-Saharan Africa	6	15	16	1.05
World market prices (US\$/mmt):				
Rice	186	299	296	-0.80
Wheat	109	205	209	1.76
Maize	91	180	181	0.46
Other grains	68	108	108	0.08
Millet	255	310	312	0.62
Sorghum	93	169	172	1.72
Potato	213	210	206	-1.62
Sweet potato and yam	470	405	398	-1.53
Cassava	65	58	59	0.99
Beef	1 917	2 521	2 548	1.06
Pork	906	1 226	1 236	0.86
Sheep and goat	2 705	2 782	2 780	-0.09
Poultry	1 196	1 661	1 684	1.39

Note: * Percentage change with respect to the 2050 (SRES B2) climate change simulation.

may decrease in certain regions. Higher temperatures during the growing season in low-latitude regions, where such temperature-induced yield loss cannot be compensated fully by the fertilization effects of higher CO₂ levels, will adversely affect food production.

Similar to grain prices, in the 2050 (SRES B2) climate change simulation meat prices

are expected to increase (Table 9.8). Livestock prices are expected to increase as a result of higher animal feed prices and rapidly growing meat demand. Even though sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both climate change adaptation scenarios focusing on the region are projected to reduce world food prices. Under this scenario, world food prices decline between 0.8 and 1.6 per cent for rice, potatoes, sweet potatoes and yams. Reductions in world market prices for both cereals and meat are more pronounced in IMPACT than in GTAP-W.

Adaptation Scenario 2: Improvements in Agricultural Productivity

Improvements in agricultural productivity in both rainfed and irrigated agriculture enable farmers to obtain higher levels of output per unit of input. Table 9.9 shows an increase in total crop production but the magnitude differs by crop type. The 'other agricultural products' sector is the sector with the highest increase in production (25 per cent), followed by oilseeds; wheat; and vegetables, fruits and nuts (17, 16, and 11 per cent, respectively). Rainfed and irrigated production increase for all crops with the exception of rainfed sugarcane.

Higher levels of agricultural productivity result in a decline in production costs and consequently in a decline in market prices. Table 9.9 shows, for all crop types, a decrease in domestic and world market prices. A 25 per cent increase in agricultural productivity leads to a reduction of around 10 to 13 per cent in domestic market prices; only sugarcane experiences a smaller decline, at 8 per cent. World market prices, in turn, decline by 3 to 4 per cent. This scenario results in a decline in the number of malnourished children of 1.6 million children, which is close to the no climate change simulation (Figure 9.4). Thus improving crop yields in both rainfed and irrigated areas is a strategy that would almost completely offset the impact of climate change on child malnutrition.

Total production in non-agricultural sectors is also affected under this scenario. Reductions in total production are more pronounced for energy-intensive industries, other industries and services as well as gas (4.8, 4.1 and 3.7 per cent, respectively). The food products sector is affected positively and its production increases by 1.4 per cent. Domestic and world market prices increase for all nonagricultural sectors except for food products.

An increase in agricultural productivity reduces the demand (at constant effective prices) for rainfed land, irrigated land and irrigation. Therefore market prices for these three factors decrease (12.4, 41.7 and 39.9 per cent, respectively). Changes in market prices for the rest of the factors are positive. Returns to unskilled labor increase more than returns to skilled labor (3.0 and 2.4 per cent, respectively) (Table 9.9). Thus an increase in agricultural productivity benefits both agricultural and non-agricultural households, as suggested by FAO (2006). Regional welfare and real absorption reveal that sub-Saharan Africa benefits from the higher agricultural yields scenario. Regional welfare increases by US\$15.4 billion and real absorption by US\$32.5. This adaptation scenario promotes GDP growth by 1.5 per cent (US\$25.7 billion), which more than offsets the initial reduction of 0.2 per cent in GDP due to climate change as projected under the SRES B2 baseline simulation (US\$3.3 billion), but not the cumulative investment costs required for improving agricultural yields in sub-Saharan Africa.

Table 9.9 Improvements in agricultural productivity: Percentage change in the demand for endowments, total production and market price in sub-Saharan Africa (results from GTAP-W)

GTAP-W sectors	Change in demand for endowments (%)						Change in Production (%)			Change in market price (%)	Change in world market price (%)*		
	Irriga- tion	Irrigated land	Rainfed land	Pasture land	Unskilled labor	Skilled labor	Capital	Natural resources	Irrigated			Rainfed	Total
1 Rice	-5.10	-5.24	-12.21		-3.00	-2.85	-2.88		18.50	1.58	2.03	-13.51	-2.82
2 Wheat	6.06	5.89	-1.90		11.31	11.48	11.38		32.42	15.40	16.13	-10.14	-2.56
3 Cereal grains	-4.98	-5.13	-12.12		-2.87	-2.73	-2.77		18.63	2.21	2.29	-13.60	-3.32
4 Vegetables, fruits, nuts	1.99	1.83	-5.66		6.04	6.21	6.15		27.34	10.88	10.95	-12.77	-2.60
5 Oilseeds	6.44	6.27	-1.55		11.80	11.97	11.92		32.90	16.82	16.93	-12.90	-2.91
6 Sugarcane, sugar beet	-5.13	-5.28	-12.25		-3.06	-2.91	-2.96		18.45	-0.10	1.21	-7.52	-2.81
7 Other agricultural products	12.55	12.37	4.09		19.79	19.97	19.92		40.52	25.22	25.24	-11.58	-4.15
8 Animals				0	0.36	0.51	0.45				0.06	3.65	0.78
9 Meat					-3.29	-2.59	-2.70				-2.96	2.86	0.17
10 Food products					1.00	1.73	1.61				1.38	-1.72	-0.99
11 Forestry					-0.06	0.06	0.03	0.00			0.02	2.49	0.67
12 Fishing					1.28	1.41	1.36	0.01			0.51	5.51	0.76
13 Coal					-1.74	-1.62	-1.61	-0.01			-1.25	0.99	0.43
14 Oil					-2.86	-2.73	-2.75	-0.01			-2.35	0.67	0.36
15 Gas					-5.02	-4.64	-4.47	-0.01			-3.70	0.84	0.33
16 Oil products					-2.00	-1.21	0.47				0.41	1.13	0.32
17 Electricity					-2.50	-1.71	-1.51				-1.47	2.09	0.22
18 Water					-0.52	0.29	0.28				0.14	2.12	0.15
19 Energy-intensive industries					-5.57	-4.85	-4.81	0.00			-4.81	1.93	0.14
20 Other industries and services					-4.50	-3.73	-3.81				-4.14	1.43	0.09
21 Market services					-0.83	0.07	0.07				-0.30	2.09	0.12
22 Nonmarket services					0.04	0.85	0.79				0.57	1.68	0.12
Change in market price (%)	-39.86	-41.70	-12.44	4.58	3.03	2.38	2.49	1.83					

Notes:

Percentage change with respect to the 2050 climate change simulation.

* World price index for total supply.

Table 9.10 Improvements in agricultural productivity: regional production and world market prices for cereals and meat in 2050 climate change simulations (results from IMPACT)

Description	2050		Percentage change*
	Climate change simulation	Increase crop yield	
Cereal production (mmt):			
North America and Europe	1 188	1 156	-2.73
Central West Asia and North Africa	240	227	-5.41
East and South Asia and Pacific	1 010	987	-2.29
Latin America and Caribbean	262	254	-3.05
Sub-Saharan Africa	211	254	20.29
Root and tuber production (mmt):			
North America and Europe	198	196	-0.88
Central West Asia and North Africa	48	47	-1.21
East and South Asia and Pacific	371	361	-2.91
Latin America and Caribbean	107	101	-4.99
Sub-Saharan Africa	379	441	16.27
Meat production (mmt):			
North America and Europe	122	123	0.90
Central West Asia and North Africa	33	33	0.91
East and South Asia and Pacific	202	205	1.31
Latin America and Caribbean	82	84	2.38
Sub-Saharan Africa	15	16	4.30
World market prices (US\$/mmt):			
Rice	299	279	-6.58
Wheat	205	190	-7.50
Maize	180	153	-15.05
Other grains	108	85	-21.46
Millet	310	228	-26.41
Sorghum	169	130	-23.07
Potato	210	190	-9.37
Sweet potato and yam	405	286	-29.39
Cassava	58	40	-30.75
Beef	2 521	2 507	-0.54
Pork	1 226	1 213	-1.04
Sheep and goat	2 782	2 752	-1.09
Poultry	1 661	1 642	-1.18

Note: * Percentage change with respect to the 2050 (SRES B2) climate change simulation.

Higher rainfed and irrigated crop yields in IMPACT result in higher food production, which lowers international food prices, making food more affordable for the poor. Table 9.10 shows an increase in cereal production by around 20 per cent; meat production increases by 4 per cent. As expected, world market prices for all cereals and meat

products decrease much more under this second adaptation scenario. Prices decline, between 15 and 31 per cent, particularly for those crops that are of primary importance for sub-Saharan Africa: roots and tubers, maize, sorghum, millet and other coarse grains. As in the former adaptation scenario, the reductions in world market prices are more pronounced in IMPACT than in GTAP-W.

DISCUSSION AND CONCLUSIONS

In this chapter, we first present an overview of general equilibrium models that can be used to assess the impact of climate change on agriculture at the national and global levels. We then present results for sub-Saharan Africa based on a global CGE model that explicitly incorporates rainfed and irrigated agriculture as factors of production. Data for this disaggregation have been obtained from a global partial equilibrium agricultural sector model, IMPACT, which allows for improved calibration and enhanced policy insights.

The methodology combines the advantages of the two types of models. IMPACT considers detailed water–agriculture linkages and provides the data underlying GTAP-W. While IMPACT can provide results for water and food supply in 281 FPU, the model cannot examine impacts on non-agricultural sectors. As in all CGE models, GTAP-W takes into account the linkages between agricultural and non-agricultural sectors as well as a full treatment of factor markets. GTAP-W considers water quantity and prices but ignores the non-market benefits and costs of water use. For instance, the model is unable to predict the direct ecological impact of excessive pumping that reduces groundwater and affects the flow of streams, but increases the market-based benefits from water use.

A series of analyses using a no climate change and a climate change scenario are summarized in Table 9.11.

Without specific adaptation, climate change would have a negative impact on agriculture in sub-Saharan Africa. Total food production would fall by 1.6 per cent, with heavy losses in sugarcane (–10.6 per cent) and wheat (–24.1 per cent). The number of malnourished children would increase by almost 2 million.

The first adaptation scenario doubles the irrigated area in sub-Saharan Africa compared to the 2050 (SRES B2) climate change simulation, but keeps total crop area constant in both models. The second adaptation scenario increases both rainfed and irrigated crop yields by 25 per cent for all countries in sub-Saharan Africa.

Because of the relatively low share of irrigated area in total agricultural area in sub-Saharan Africa, an increase in agricultural productivity achieves much larger benefits for the region than a doubling of irrigated area. Because agriculture in sub-Saharan Africa is far below its potential, substantial productivity gains are technically feasible. The differences between the adaptation scenarios are more pronounced in GTAP-W than in IMPACT. Both adaptation scenarios increase total crop production, but the magnitude differs according to crop type.

An increase in irrigated area and agricultural productivity leads to a decrease in the production cost of agricultural products and, consequently, to a reduction in market

Table 9.11 Summary of the impact of climate change and adaptation on sub-Saharan Africa

Description	2050 No climate change simulation	2050* Climate change simulation	2050** Double irrigated area scenario	2050** Increase crop yield Scenario
Total production (thousand mt)	1 250 491	-1.5%	0.1%	18.0%
Rainfed production (thousand mt)	1 074 930	0.7%	-0.6%	17.9%
Irrigated production (thousand mt)	175 561	-15.3%	99.5%	23.4%
Total area (thousand ha)	246 363	-0.7%	0.0%	0.0%
Rainfed area (thousand ha)	235 169	-0.6%	-4.8%	0.0%
Irrigated area (thousand ha)	11 194	-3.5%	100.0%	0.0%
Annual investment costs (US\$ million)			2 841	2 686
Change in welfare (US\$ million)	—	1 786	119	15 435
Change in real absorption (US\$ million)	—	17 588	45	32 499
Change in GDP (US\$ million)	—	-3 333	113	25 720
Change in GDP (percentage)	—	-0.2%	0.0%	1.5%
Malnutrition (million children)	30.2	32.0	31.7	30.4

Notes:

* Percentage change with respect to the 2050 no climate change simulation.

** Percentage change with respect to the 2050 (SRES B2) climate change simulation.

prices. Even though sub-Saharan Africa is not a key contributor to global food production or irrigated food production, both adaptation scenarios help lower world food prices. Both GTAP-W and IMPACT show more pronounced reductions in domestic and world market prices under the scenario simulating enhanced crop productivity.

Lower food prices make food more affordable for the poor. As a result the number of malnourished children in sub-Saharan Africa is projected to decline by 0.3 million children by 2050 under the doubling of irrigated area scenario, and by 1.6 million children under the increased agricultural productivity scenario. The reduction in the number of malnourished children under enhanced crop productivity almost equals the increase in the projected number of malnourished children under the climate change simulation compared to a simulation without climate change.

Changes in total production in non-agricultural sectors have a mixed pattern; however, all of them show an increase in domestic and world prices. An exception is the food products sector, in which prices decline because production is promoted by a higher supply and lower price of agricultural products.

Both adaptation scenarios enable farmers to achieve higher yields and revenues from crop production. The increase in regional welfare and absorption in the first scenario are modest but in the second scenario reach US\$15.4 billion and US\$32.5 billion, respectively.

The efficacy of the two scenarios as adaptation measures to cope with climate change is measured by changes in regional GDP. An increase in agricultural productivity widely exceeds GDP losses due to climate change, but investment costs are considerable. GDP increases by US\$25.7 billion compared to the initial reduction in GDP of US\$3.3 billion.

On the other hand, the increase in GDP as a result of irrigation expansion alone cannot offset GDP losses and is far below investment requirements. (GDP increases by only US\$113 million.) While these results are promising in terms of the potential to develop investment programs to counteract the adverse impacts of climate change, the scenario implemented here, SRES B2, is on the conservative side of the range of climate change scenarios.

Several caveats apply to the above results. First, we implicitly assume, for the expansion of irrigated agriculture, the availability and accessibility of water resources. We also assume sustainable use of water resources. Second, because regional and sectoral resolutions are crude, the analysis cannot be used directly for advice on national let alone local water policy. Third, we have made no attempt to address uncertainty in our scenarios. We use only one SRES scenario, which could generate biased estimates. More analysis is needed to cope with the uncertainty of climate change, which could include stochastic simulation approaches. Fourth, we use averages for world regions; we do not take into account differences between river basins within the same world region or country. These local effects are averaged out. Moreover, given that many of the adverse impacts of climate change on agriculture will probably come from the intensification and increased frequency of extreme events such as droughts and floods, more work is needed to better analyze the long-term impacts of such extreme events on crop productivity and human welfare, particularly for world regions that are least likely to cope with adverse impacts of climate change such as sub-Saharan Africa.

ACKNOWLEDGMENTS

We had useful discussions about the subjects addressed in this chapter with Siwa Msangi, Mark Rosegrant and Timothy Sulser from IFPRI. The writing of this chapter was supported by the Federal Ministry for Economic Cooperation and Development, Germany, under the project 'Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa', which forms part of the Consultative Group on International Agricultural Research (CGIAR) Challenge Program on Water and Food, and by the Michael Otto Foundation for Environmental Protection.

NOTES

1. The GTAP model is a standard CGE static model distributed with the Global Trade Analysis Project (GTAP) database of the world economy (www.gtap.org). For detailed information, see Hertel (1997) and the technical references and papers available on the GTAP website.
2. Burniaux and Truong (2002) developed a special variant of the model, called GTAP-E. The model is best suited for the analysis of energy markets and environmental policies. There are two main changes in the basic structure. First, energy factors are separated from the set of intermediate inputs and inserted into a nested level of substitution with capital. This allows for more substitution possibilities. Second, the database and model are extended to account for CO₂ emissions related to energy consumption.
3. See Appendix A for the regional and sectoral aggregation used in GTAP-W and IMPACT.
4. Let us assume that 60 per cent of total rice production in region *r* is produced on irrigated farms and that the returns to land in rice production are US\$100 million. Thus we have for region *r* that irrigated land rents in rice production are US\$60 million and rainfed land rents in rice production are US\$40 million.

5. Let us assume that the ratio of irrigated yield to rainfed yield in rice production in region r is 1.5 and that irrigated land rents in rice production in region r are US\$60 million. Thus we have for irrigated agriculture in region r that irrigation rents are US\$20 million and land rents are US\$40 million.
6. A sensitivity analysis was performed and revealed that the model results are not sensitive to changes in the value of the elasticity of substitution between land and irrigation.
7. As described in the (SRES) (IPCC, 2000), the B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with a slowly but continuously increasing global population and intermediate levels of economic and technological development. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

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APPENDIX A

Table 9A.1 Regional and sectoral mapping between IMPACT and GTAP-W

16 GTAP-W regions	115 IMPACT regions
USA	USA
Canada	Canada
Western Europe	Alpine Europe, Belgium and Luxembourg, British Isles, Cyprus, France, Germany, Iberia, Italy, Netherlands, Scandinavia
Japan and South Korea	Japan, South Korea
Australia and New Zealand	Australia, New Zealand
Eastern Europe	Adriatic, Central Europe, Poland
Former Soviet Union	Baltic, Caucasus, Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Middle East	Gulf, Iran, Iraq, Israel, Jordan, Lebanon, Syria, Turkey
Central America	Caribbean Central America, Mexico
South America	Argentina, Brazil, central South America, Chile, Colombia, Ecuador, northern South America, Peru, Uruguay
South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
Southeast Asia	Indonesia, Malaysia, Mongolia, Myanmar, North Korea, Philippines, Singapore, Southeast Asia, Thailand, Vietnam
China	China
North Africa	Algeria, Egypt, Libya, Morocco, Tunisia
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo, Djibouti, Democratic Republic of the Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
Rest of the world	Papua New Guinea, rest of the world
7 GTAP-W crops	23 IMPACT crops
Rice	Rice
Wheat	Wheat
Cereal grains	Maize, millet, sorghum, other grains
Vegetables, fruits, nuts	Potato, sweet potatoes and yams, cassava and other roots and tubers, vegetables, (sub)tropical fruits, temperate fruits, chickpeas, pigeon peas
Oilseeds	Soybeans, oils, groundnuts
Sugarcane, sugar beet	Sugarcane, sugar beets
Other agricultural products	Other
–	Meals, cotton, sweeteners

APPENDIX B: THE SUBSTITUTION ELASTICITY OF WATER

Let us assume that there is a production function

$$Y = f(X, W) \quad (9A.1)$$

where Y is output, W is the irrigation water input, and X is all other inputs (e.g. land). The cost of production

$$C = pX + tW \quad (9A.2)$$

where t is the price of water and p is the composite price of other inputs. Production efficiency implies

$$\frac{f_X}{f_W} = \frac{p}{t} \quad (9A.3)$$

Let us assume that (9A.1) is CES

$$Y = (X^{-\rho} + W^{-\rho})^{\frac{-1}{\rho}} \quad (9A.1')$$

This implies

$$\frac{f_X}{f_W} = \frac{W^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \quad (9A.3')$$

From Rosegrant et al. (2002), we know the price elasticity of water use, η (estimates for 15 regions). Thus we have

$$\frac{W_1^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \text{ and } \frac{W_2^{\rho+1}}{X^{\rho+1}} = \frac{p}{t(1 + \delta)} \text{ imply } W_1^{\rho+1} = W_2^{\rho+1}(1 + \delta) \quad (9A.4)$$

That is, the price elasticity η implies the substitution elasticity ρ , for any price change δ :

$$\rho = - \frac{\ln(1 + \delta)}{\ln(1 + \eta\delta)} - 1 \quad (9A.5)$$

10 Integrated assessment models – the interplay of climate change, agriculture and land use in a policy tool

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INTEGRATED ASSESSMENT MODELING

Integrated assessment (IA) models have become a common tool for assessing strategies to cope with climate change. They describe the complex relations between environmental, social and economic factors that determine future climate change and the effectiveness of climate policy, in order to derive policy-relevant insights (e.g. Schneider, 1997; Hope, 2005). Working Group III of the Second Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) acknowledged the rising importance of IA models by devoting a chapter to them, including a survey by Weyant et al. (1996). We begin the chapter describing the interplay of climate change and land-use activities in IA models with a brief overview on the history of IA modeling, followed by a discussion of common characteristics of and differences between IA models, as well as their application as a policy tool. We conclude this introductory section by providing an outline of a typical IA model structure, and focusing the land-use module as the main subject of further investigation by putting it into the center.

History

With increasing indication of anthropogenic causation of global warming, the integrated assessment of climate change became a fast-expanding field of scientific interest and policy relevance at the end of the 1980s. The generally recognized intricate features of climate change and the emerging need for policy response have triggered substantial research activities over the past two decades. Initial efforts by a handful of research groups (Edmonds and Reilly, 1985; Rotmans, 1990; Manne and Richels, 1992) were boosted by an international conference at the MIT (Dornbusch and Poterba, 1991) and a series of workshops held at the International Institute for Applied Systems Analysis (IIASA) between 1992 and 1996 (see Kaya et al., 1993; Nakićenović et al., 1994) which initiated a sustained engagement in the integrated assessment of climate change.

Early IA models typically only included atmospheric CO₂ concentration and temperature change as environmental variables. They attempted to adopt and improve traditional decision-analytical frameworks. Examples include the early applications of cost–benefit analysis by Nordhaus (1991, 1994) and Cline (1992). Gradually, more physical detail was added to IA models (e.g. Mintzer, 1987; Rotmans, 1990). Later, emphasis was put on

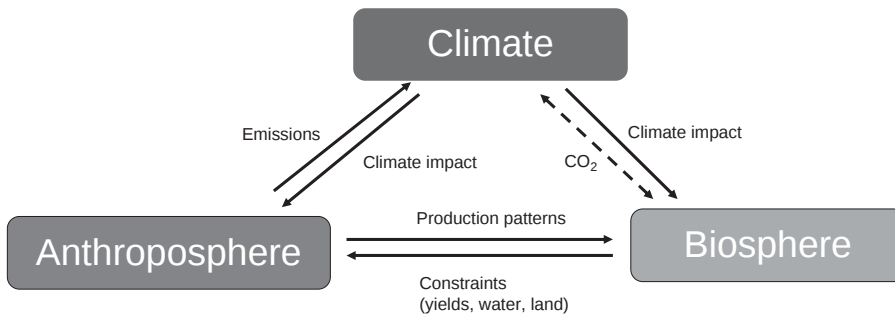


Figure 10.1 General structure of integrated assessment models

selected aspects of climate change, and resulted in efforts aimed at creating frameworks specifically tailored to the climate change problem. For example, uncertainty has attracted attention and is the key concern in the contributions by Dowlatabadi and Morgan (1993) and by the group at the University of Cambridge (Hope et al., 1993, Plambeck et al., 1997). Meanwhile, a substantial number of IA models have been developed (see also Schneider, 1997 for an overview of the development history, and Toth, 2003 and van Vuuren et al., 2011 for summaries). Van der Sluijs (2002) has already listed more than 50 climate change IA models. Over the last decade some IA models have expanded their coverage by considering land-use and terrestrial carbon cycle representation, non-CO₂ gases and air pollutants, and by looking into specific impacts of climate change (e.g. on water and human health).

Definition

Integrated assessment modeling is distinguished by its holistic approach in representing causes and effects of climate change. The modeling is *integrated* because it crosses the borders between academic disciplines and integrates knowledge from two or more domains into a single framework. IA modeling relies on the use of numerical *models* and is referred to as *assessment* because it aims at generating useful information for policy making rather than advancing knowledge for its own sake (http://en.wikipedia.org/wiki/Integrated_assessment_modelling).

In general, IA models are composed of modules that cover essential parts of the anthroposphere, the biosphere and the climate system (see Figure 10.1). A typical cause–effect chain of climate change starts from economic activities, and then translates emissions into changes in climate and related impacts on ecosystems, human health and agriculture for example, including various feedbacks between these elements. As IA models aim at integrating different disciplines, they run the risk of becoming extremely complex. In order to make their construction and use tractable, many IA models use relatively simple equations to capture relevant phenomena.

Classification

Based on the pioneering work of Edmonds and Reilly (1985), Rotmans (1990) and Nordhaus (1991), three different development branches of IA models and paradigms

have evolved. Each of them puts a different domain at the center. Nordhaus built his DICE model around an economic growth model, Edmonds started the construction of the MiniCAM model from an energy system model and Rotmans designed the IMAGE model based on a comparatively detailed description of the biophysical system. These development branches provide a classification that still holds. Goodess et al. (2003) and van Vuuren et al. (2011) distinguish between IA models that have a stronger focus on economics and other IA models that are more focused on the physical processes in both the natural system and the economy. Examples of the former are models focusing on cost–benefit analysis and multisectoral computable general equilibrium models that are combined with climate modules. The latter are represented by integrated structural models and biophysical impact models.

IA models can also be classified into policy evaluation and policy optimization models. Examples of policy evaluation models include IMAGE (Alcamo et al., 1998b). Policy evaluation models are simulation models that calculate the implications of a user-defined policy (e.g. emission scenario) for all explicitly modeled variables of interest to the policy maker: temperature change, ecosystem and agricultural yield changes and sea-level rise, for example. Simulation models cannot say anything directly about the optimality features (environmental effectiveness, cost efficiency, social equity) of the user-defined scenarios, but offer the opportunity to compare any number of scenarios and derive policy implications (Toth, 2003, p. 9). Policy optimization models restrict the range of externally defined parameters by separating key policy variables that control the evolution of the climate–economy system (e.g. emission levels, carbon taxes), and determine the values of these policy variables in an optimization procedure according to clearly defined objectives.

Policy optimization models can run in a cost–benefit framework such as the RICE/DICE family of models (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) or in a cost-effectiveness framework such as the MERGE model (Manne et al., 1995). The former determines optimal values for both the costs of mitigation and impacts. Recent attempts successfully include adaptation in the assessment (Hof et al., 2010). In a cost-effectiveness framework the acceptable impact is specified as an environmental target (emission budget target, CO₂-equivalent concentration and temperature target) and the optimization is restricted to finding the least-cost emission path to achieve that target. A new decision and assessment framework that incorporates elements of the policy evaluation and the policy optimization framework is the Tolerable Windows Approach (Bruckner et al., 1999; Toth et al., 2003). Its distinctive feature is the ability to demarcate a range of permitted emission paths according to externally specified combinations of impact and mitigation cost ceilings.

Policy Tool

IA models' main goal is to support policy making. Policy issues addressed by IA models include determining global and regional costs and benefits of reducing future GHG emissions, identifying cost-effective emission reduction pathways to reach certain climate targets, as well as investigating the type of mitigation measures required for achieving a particular target and describing the economic impacts of certain climate policies. IA models are also applied to address potential conflicts that arise from climate policies

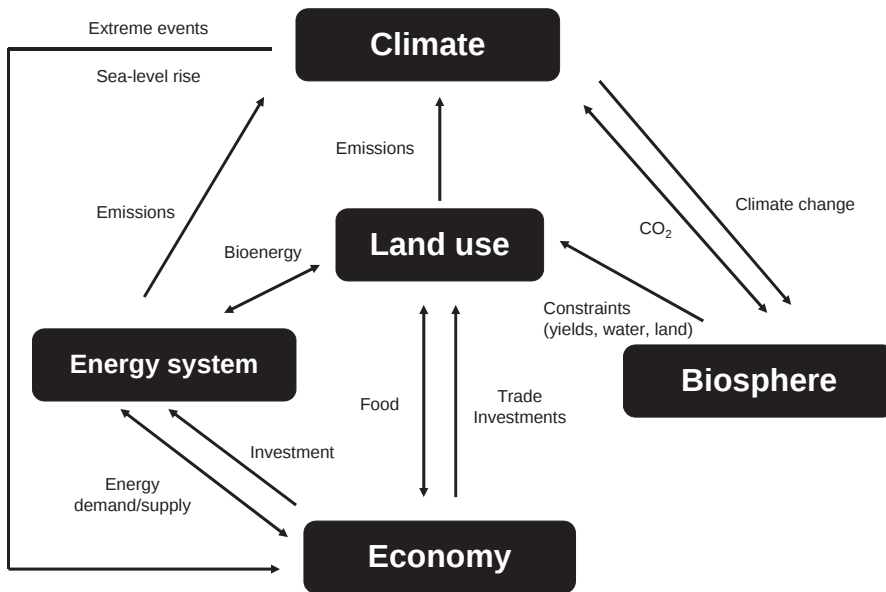


Figure 10.2 Interlinkages of the land-use module with other modules of an IA model

that have contrary impacts across regions and across different domains. IA models support negotiations on environmental agreements and climate protocols by analyzing the perspectives and implications of international burden sharing of mitigation policies. Furthermore, they address tradeoffs between the costs and social benefits of climate change mitigation and identify areas where adaptation policies are needed. Particular policy support is given by investigating promising policy instruments (e.g. cap-and-trade system, carbon taxes, technology protocols, green certificates).

Components

Figure 10.1 provides an overview of the basic structure of an IA model composed of the anthroposphere (or socioeconomic module) that can be considered as the driver of climate change, the climate system module that reacts to this driver and the impact module that is composed of a variety of natural system elements (mainly the biosphere). While the primary cause–effect chain reaches from the socioeconomic system to the climate system and to the impact system and back to the socioeconomic system, there are a number of feedbacks that, for example, directly link back from the climate system to the socioeconomic system, and from the biosphere to the climate system.

For the discussion in the next section we decompose the basic structure. Within this decomposed structure (see Figure 10.2), the land-use system plays a central role. It connects all other parts. Moreover, the socioeconomic system is divided into an economy and an energy system sub-module. Both are linked by the demand of the economy for final energy. This demand has to be met by energy production within the energy system, which needs capital for investments in order to install capacities for energy production. In general, the energy system modules of IA models do not include capital markets.

Therefore the demand for investments has to be met via a link to the economy module (Bauer et al., 2008). Depending on the choice of technology, energy production causes greenhouse gas emissions (above all CO₂) that enter the climate system. Induced climate changes lead to climate impacts (e.g. extreme events, sea-level rise) that feed back into the socioeconomic system. Climate change also impacts the biosphere by changed precipitation patterns, increased temperature and CO₂ fertilization. This may cause changes in ecosystems, biodiversity, agriculture and the availability of land and water. Such changes in the biosphere feed back into the climate system by processes like soil erosion, biome shifts and albedo changes. All linkages of the land-use system shown in Figure 10.2 will be discussed in more detail in the following section.

In general, reduced-form models are used for each of the components of an IA model. Nevertheless, the range of complexity covered in IA models is rather broad. Monolithic models, programmed in the same programming language with a hard link between the represented modules, accompany distributed models composed of soft-linked modules. Recent research efforts (Leimbach and Jaeger, 2004; Bahn et al., 2006; Warren et al., 2008) propagate a modular approach to integrated assessment modeling.

With respect to implementation, both traditional approaches of model coupling have specific challenges. The hard-link approach results in the most consistent representation of the coupled system. However, the system is hard-wired. Transparency decreases and numerical efforts and maintenance demand increase. Consequently, the number and complexity of modules that can be coupled is limited. The soft-link approach can generally combine more modules. Nevertheless, the task of coordinating the communication and data flow between the modules is demanding. Feedbacks that, for instance, represent the process of balancing demand and supply require an iterative approach. Since capturing feedback effects is most challenging for the soft-coupling approach, links between two modules are often represented by a one-way link only.

AGRICULTURE AND LAND USE IN INTEGRATED ASSESSMENT MODELS

Dimensions of Agriculture and Land-use Modeling

Within IA studies the treatment of agriculture and land-use change is of special importance for several reasons. Agriculture plays a major role in the use of scarce physical resources like land and water. It is also one of the economic sectors potentially most strongly affected by climate change. This is of special relevance to low-income countries where agriculture contributes a large share to GDP. Moreover, agriculture and land-use change account for about a third of total global GHG emissions. Hence the sector is relevant for the design of climate policies, mitigation strategies and economic development. However, the development of coherent emission mitigation policies for the agricultural sector poses particular difficulties due to different types of agents and emissions.

Agricultural land-use patterns are determined by a multitude of environmental, economic and sociocultural conditions and their interactions. The competition between different types of land-use is a crucial issue (Lotze-Campen et al., 2010). Regional studies have illustrated the importance of land-use competition between agricultural and

forestry GHG mitigation (Murray et al., 2005). As for IA models, few models exist that explicitly integrate a land-use sector and model land competition endogenously (Sands and Leimbach, 2003). The challenge of projecting future land-use patterns is to account, within one modeling framework, for the socioeconomic determinants of agricultural demand as well as for the spatial heterogeneity of the land's suitability for agricultural production. Land suitability for agricultural production is largely determined by environmental conditions (e.g. climate conditions, soil quality, water availability), but also by socioeconomic factors such as management practices, technological development and property rights. Biophysical processes of plant growth that form the basis of yield estimations are modeled in some detail in a number of IA land-use modules. Therein, water uptake and nutrient fluxes play an important role. Requirements on land suitability including the environmental conditions are quite different between different crop types as well as between crop production and livestock farming. Taking these differences into account, IA models are able to mimic climate change adaptation policies by shifts in cultivation.

Demand for land-based products, like food, feed, fiber and forest products, is determined by the number of consumers and their per capita consumption, which is dependent on their income, market access and cultural background. Demand in the models is split into a range of different primary agricultural products, in particular crop types, as well as processed products.

International trade in agricultural commodities plays an important role in the allocation of limited land and water resources to the most efficient use, according to comparative advantage. However, agricultural trade is also constrained by a variety of policy goals such as food security, national self-sufficiency in food, protection of farm incomes and maintenance of certain cultural landscapes shaped by farming activities. The key role of national and international farm policies has to be taken into account in IA studies with a strong focus on agriculture and land-use.

Lotze-Campen (2008) provides an overview of different land-use modeling approaches in the context of integrated assessments. The disciplines involved in studying land-use change processes differ significantly in methodologies and data used. Economic sector models (cf. Hertel et al., 2009) typically operate with administrative units, that is, countries or regional groups of countries in the case of global models. They usually provide little spatial detail on agricultural production and resource constraints. Biophysical models, on the other hand, typically operate on geographic grids. These divide the terrestrial land area into distinct spatial units that are exactly localized. For projecting future land-use patterns, the spatial heterogeneity of land suitability and water availability, which is largely captured by highly resolved geographic grids, is an important factor that strongly determines the size of agricultural area (Müller et al., 2006). The economic structure of land-use models has to harmonize country-level information on agricultural demand and trade flows with gridded information on local production conditions for various crops.

Currently available IA models differ in three dimensions with regard to agriculture and land-use: the level of detail in covering biogeochemical processes and conditions; the level of detail in covering socioeconomic processes and conditions; and the explicit coverage and detail of links and interactions between the two spheres. In a later section we provide four examples of how agriculture and land-use change are implemented in

different modeling approaches, but we now focus on major interfaces of the land-use system in IA models.

The Climate System Interface

The agricultural system is based on biogeochemical cycles that are influenced by climate, hydrology and soil conditions, but also by human activities. The climate system comprises atmospheric processes, and carbon flows between the ocean, the atmosphere and the terrestrial biosphere. The climate system interface includes all climate-related natural conditions that favor or hinder the growth of agricultural crops, e.g. temperature, CO₂ concentration and precipitation. However, it also includes all feedbacks from the land-use system to the climate system, that is, GHG emissions, albedo, evapotranspiration and carbon uptake.

Plant growth and crop yields will be both positively and negatively affected by climate change. Diverging effects are caused by rising CO₂ concentrations, higher temperature and changing precipitation patterns, changes in water availability, increased frequency of weather extremes such as floods, heavy storms and droughts, soil erosion and other environmental changes. While some of these impacts have been studied separately in a detailed way, IA models that include an agricultural and land-use module take most of these interactions with the climate system into account at least in a reduced form. However, complex interactions between different factors and especially extreme events are still not well understood and therefore are highly underrepresented in any IA model.

Climate impacts on agriculture

Yields of most agricultural crops increase under elevated CO₂ concentration. Free air carbon enrichment (FACE) experiments indicate productivity increases in the range of 15–25 per cent for C3 crops (like wheat, rice and soybeans) and 5–10 per cent for C4 crops (like maize, sorghum and sugar cane). Higher levels of CO₂ also improve water-use efficiency of both C3 and C4 plants. However, the experiments do not address important co-limitations due to water and nutrient availability. Some studies expect much less favorable crop response to elevated CO₂ in practice than asserted on experimental sites (e.g. Long et al., 2006), while others agree with previous findings (Tubiello et al., 2007). Thus the magnitude of the positive effect due to enhanced CO₂ concentration is still uncertain (Parry et al., 2004, p. 55; Easterling et al., 2007, p. 282). Only few crop modeling approaches are capable of reproducing the complex interactions between CO₂, crop water use and yields (see below).

Higher temperatures are to be expected in the future over the entire globe, but with significant regional and seasonal variations. In the Northern hemisphere in higher latitudes rising temperatures imply lengthening of the growing season (Gitay et al., 2001). This allows earlier planting of crops in spring, earlier maturing and harvest and the possibility for two or more cropping cycles. An expansion of suitable crop area may become possible in the Russian Federation, North America, Northern Europe and East Asia. In contrast, significant losses are predicted for Africa due to heat and water stress and an increase of arid and semi-arid regions (Fischer et al., 2005). In the tropics, additional warming of less than 2 °C will already lead to crop yield losses, while crops in temperate

regions will broadly benefit from temperature increases of up to 2 °C (Easterling et al., 2007).

Agriculture highly depends on *water availability*. More than 80 per cent of global cropland is rainfed, but irrigated cropland with an area share of 16 per cent produces about 40 per cent of the world's food. Agricultural irrigation accounts for around 70 per cent of global freshwater withdrawals (Gitay et al., 2001). Due to growing global food demand and rising temperature, even more water will be required in the future. Climate impacts on crop productivity will fundamentally depend on precipitation changes. Precipitation projections show large variability of quantity and distribution, which poses a challenge to IA modeling (Solomon et al., 2007). The decline in water availability will affect areas currently suitable for rainfed crops like the Mediterranean basin, Central America and sub-tropical regions of Africa and Australia (Easterling et al., 2007). While irrigated agriculture is expected to become more important, water supply may be insufficient (Döll, 2002). Only a few IA models include a sufficiently elaborate hydrology component to capture the explicit links between water use in agriculture and other sectors as well as water availability.

Climate variability, that is, extreme climate events such as heat waves, heavy storms, floods or droughts, may damage crops in specific development stages. Heavy rainfall in some regions as well as increasing frequency and duration of warm weather extremes in others are to be expected. In many regions, especially in the tropics and sub-tropics, droughts have been longer and more intensive since the 1970s because of higher temperatures and less precipitation (Solomon et al., 2007). Climate change will deepen these trends. In arid and semi-arid regions, higher rainfall intensity will increase risks of soil erosion and salinization. However, these issues are currently not covered in the available IA modeling approaches.

GHG emissions related to agriculture and land-use change

While assessing climate change impacts on the agricultural sector is one specific motivation to include agriculture and land-use modules in IA models, accounting for *land-use-related emissions* is another. As a contributor to climate change, agriculture currently accounts for approximately 14 per cent of total global anthropogenic GHG emissions. The sector is responsible for about 47 per cent of total anthropogenic emissions of methane (CH₄) and 58 per cent of nitrous oxide (N₂O) (IPCC, 2007), whereas the contribution of agriculture to CO₂ emissions is negligible (US-EPA, 2006; IPCC, 2007; Stern, 2006). CH₄ is produced by anaerobic decomposition of organic matter, mainly associated with enteric fermentation of ruminants, rice cultivation and manure storage. N₂O emissions from agriculture are basically related to nitrogen fertilizers and manure applied to soils, but also manure storage. The magnitude and relative importance of the different sources and emissions vary widely between regions. Developing countries account for the major share (almost three-quarters) of agricultural emissions (Stern, 2006). As a result of ongoing population growth and rising per capita caloric intake and changing dietary preferences towards meat and dairy products, agricultural GHG emissions are expected to increase significantly in the future, especially in Asia, Latin America and Africa. Some IA models project emissions of non-CO₂ gases, while only few have detailed coverage of their impacts on the climate system as well as mitigation potentials and options in the agricultural sector.

Land-use changes are a massive source of carbon emissions and contribute significantly to global warming due to the conversion of forests into agricultural land, but also as a result of expanding settlements, infrastructure and unsustainable logging practices (Canadell et al., 2007; Gullison et al., 2007; Hansen and DeFries, 2004). Mainly tropical deforestation accounts for almost 20 per cent of current total GHG emissions (Grainger, 2008; IPCC, 2007). Avoiding deforestation in tropical countries is seen as a cost-effective option for mitigating climate change (e.g. Stern, 2006; Kindermann et al., 2008; Tavoni et al., 2007). While land expansion into forest and related CO₂ emissions is captured by a number of IA models, complex policy options for avoiding deforestation are usually not.

Various types of *bioenergy production*, mainly from cellulose-based feedstocks, have a high mitigation potential. CO₂ sequestration also provides a range of mitigation measures, for example the preservation of existing carbon stocks (permanent grasslands, forests, soils with high organic matter content like peatlands, bogs and wetlands) and carbon sequestration in mineral soils (Frelüh-Larsen et al., 2008). Other measures for CO₂ sequestration are afforestation and agroforestry. Certain bioenergy crops like short-rotation trees and perennial grasses also offer potential for CO₂ sequestration, in addition to the substitution of fossil fuels. CO₂ sequestration in mineral soils via cropland management measures (reduced tillage, diversified crop rotation systems and monitoring of carbon balances) offer less potential per area, but are not to be neglected as they are applicable on all cropland and thus amount to a high overall potential. They offer co-benefits in terms of agronomy, biodiversity and soil protection, but they suffer from specific problems and barriers of implementation such as non-permanence, uncertainty, additionality and high monitoring costs. CO₂ sequestration in mineral soils is partly overlapping with measures to reduce N₂O emissions from soils, which also can be widely implemented and offer many co-benefits for water protection and biodiversity. The mitigation potential in livestock production (mainly manure management and feeding practices) is estimated to be higher than in crop production (Smith et al., 2007). While the potential of bioenergy production is meanwhile subject to a large number of IA studies, mitigation potentials and options in crop and livestock production have been covered only by a few (e.g. Stehfest et al., 2009).

The Energy System Interface

Climate change will not only affect land-use and agriculture directly. Indirect effects emerging from different mitigation efforts in other sectors will play an important role. Growing energy demand, security of energy supply and concerns about climate change make bioenergy crops attractive for a future sustainable energy system (McLaughlin et al., 2002). Today almost all of the commercially available biofuels are produced from either starch or sugar-rich crops (for bioethanol) or oilseeds (for biodiesel). Recent research has found that these bioenergy sources are less than ideal (Crutzen et al., 2007; Searchinger et al., 2008) and turned to the use of ligno-cellulosic feedstocks such as perennial grasses and short-rotation woody crops for bioenergy production (e.g. Schmer et al., 2008; Melillo et al., 2009). A special point of interest is that scenarios aiming for low GHG concentration targets may require options within the energy sector to remove CO₂ from the atmosphere ('negative emissions'). One of the few technologies that results in

negative emissions is the combination of bioenergy and carbon capture and storage, if bioenergy can be produced in a carbon-neutral way (Hazeldine, 2009).

Recent estimates on the potential global ligno-cellulosic bioenergy supply range from less than 100 EJ/year to over 1000 EJ/year for 2050 (e.g. Berndes et al., 2003; Smeets et al., 2007; Beringer et al., 2011). The potential for bioenergy supply can be divided into three main categories: traditional bioenergy, agricultural and forest residues; and bioenergy from dedicated energy crops, where the last are the most important source of bioenergy. These estimates differ due to large discrepancies in the assumptions on land availability for biomass plantations and yield levels (including future yield improvements) in crop production. Future application of biomass for energy production is not only determined by biomass availability but also by expected demand in the energy sector and its interaction with other energy options. Commercial bioenergy has an important role in almost all IA model scenarios for future energy systems (e.g. Edenhofer et al., 2010). Massive use of bioenergy may occur in transport and as a feedstock for power, heat and hydrogen generation. In each case, the demand depends strongly on the competition with alternative climate-neutral options, particularly the hydrogen fuel cell and electric car for the transport sector, carbon capture and storage and other renewables in the power sector. Competition is based on cost estimates. In energy system models total energy production costs are composed of technology-specific investment and maintenance costs as well as fuel costs. Decisions on investments into biomass technologies are determined in IA models based on estimates on biomass fuel costs. These estimates are provided by the land-use module and include all efforts of harvesting and transporting biomass. Projected bioenergy use in the year 2100 found in most energy model scenarios is in the order of 200–300 EJ, with a minimum of 150 EJ (in a conservative reference scenario without any climate policy) and a maximum above 400 EJ (in a biomass-intensive scenario with active climate policy) (Dornburg et al., 2010).

However, as large-scale energy crop production will increase the competition for land, water and other inputs, conflicts may arise with other sustainability aspects like food security, water use and biodiversity loss (e.g. Fargione et al., 2008; Searchinger et al., 2008). First, bioenergy expansion will have mixed impacts on poor populations in urban and rural areas, as it puts an upward pressure on food prices, raises land values and potentially increases rural employment (Goldemberg, 2007). Pro-poor policies need to enhance the potential benefits and reduce the adverse impacts, particularly with regard to increasing and potentially more volatile food prices. Second, large-scale bioenergy production may affect water scarcity and quality, which are highly dependent on particular crop needs. In many regions, additional irrigation for bioenergy will further intensify existing pressures on water resources. Third, large-scale bioenergy production will have negative consequences for biodiversity (Groom et al., 2008).

All these impacts can only be studied in an integrated framework with specific implementations of models of the biosphere and the socioeconomic system. Yet only few IA models provide this detail (see below). This also applies to the tradeoff between the emission reduction effect from using biomass as an energy source against increased greenhouse gas emissions from land management and land-use change (Sands and Leimbach, 2003; Wise et al., 2009; Popp et al., 2010a). For estimating the net contribution of bioenergy to a sustainable energy mix, CO₂ emissions from fertilizer production and application, biomass conversion and trade need to be included. Furthermore, in tropical

developing countries there is an additional pressure to convert forests and peatlands into cropland. Forests are a major storage of carbon, so there is a potentially perverse impact when forest carbon is released for the purpose of bioenergy production. In addition, under increasing scarcity of productive land the growing food and bioenergy demand may only be accommodated by agricultural intensification (Smeets et al., 2009), which implies more fertilizer use and higher N₂O emissions.

The Socioeconomy Interface

Food linkage

The major purpose of land-use activities is the supply of food. Within IA models, the land-use module or an explicit agricultural module represents the land endowments, the yield characteristics and the technological evolution of the food production system. The main driver of agricultural production is the demand for food. The overall food demand depends on the number of population and on per capita income, and is therefore a variable of the economy module. Basic needs in terms of calorie requirements per capita can be used to derive a minimum overall food demand. Food intake may increase with increasing per capita income until reaching a saturation level. More sensitive, however, is the relationship between the income level and the composition of food, as the share of meat is increasing with higher incomes. This, again, is not a linear relation. On the contrary, there is some indication that at the upper end of per capita incomes, the share of meat is decreasing again. This relationship is usually analyzed across consumer groups but not across regions. Cultural and natural characteristics of regions lead to different composition of food for regions with similar per capita income level.

While the details of this relationship are hardly modeled in any of the land-use modules in existing IA models, it is a quite important relationship. Nearly as great an amount of additional emissions that can be expected from an increase in global population can be expected due to a change in the food composition in favor of meat. This also includes emissions from the conversion of land (i.e. deforestation) that is needed for livestock farming. Lifestyles, diet and related habits gain significance. An increasing share of vegetarian diet may help to reduce GHG emissions. While these aspects of the socioeconomic system are mainly subject of studies at the micro level, IA studies begin to include these issues (Stehfest et al., 2009; Popp et al., 2010b).

Investment linkage

Typically, land-use models are subject to land constraints but not to capital constraints. However, most of the yield increase in the past was not due to land expansion but due to technical progress in several parts of the agricultural production system. Land-use models that operate in a cost-minimizing mode partially consider expenditures for investments into machinery and sometimes also in R&D that induce technical progress. In most cases this remains a partial analysis that does not take the option value of these investments and alternative investments into account. Principally, however, investments within the agricultural system depend on the amount of capital available in the overall economy. Furthermore, the integration of agricultural production into the macroeconomic environment is likely to change prices that affect the agricultural sector.

Investment dynamics that result in a general equilibrium characterized by a convergence of the rates of return on capital across different sectors and across different regions can be simulated by economic growth models. Economic growth models that are part of IA models do not typically represent the agricultural sector explicitly. Hard coupling and soft coupling of the macroeconomic module and the land-use module is a challenging task as the decision horizon is generally different. Land-use models often apply recursive dynamics with myopic agents, while economic growth models represent intertemporal dynamics with agents that have perfect foresight. No IA model has yet modeled this interface in a way that general equilibrium effects are captured. In an intermediate coupling step, agents of the agricultural system are assigned with more sophisticated capabilities of expectation formation. Recent efforts have focused on integrating land-use into computable general equilibrium models (Hertel et al., 2009), thereby generating integrated models that resemble IA models.

In the context of future international climate policies, mitigation and adaptation options within the agricultural and forestry sector play an important role in finding efficient mitigation and adaptation strategies across sectors and regions, but also in financing necessary investments. Carbon markets offer a unique opportunity in particular for developing countries to take advantage of additional financial resources that could be used for investments into mitigation technologies and to reduce their vulnerability under climate change (Tubiello et al., 2009).

Beyond the need for either domestic or foreign financial capital, the agricultural system is linked to the economic sector by its demand for intermediate inputs. Input of machinery, or in economic terms the substitution of capital for labor, is an effective measure of increasing crop yields. An analogous result is achieved by the application of fertilizers (in particular nitrogen fertilizer). Detailed IA models (see below) take the application of nitrogen fertilizer into account because emissions of nitrous oxide, a major greenhouse gas, are caused by nitrogen fertilization. Due to their high-productivity impacts, the use of machines and fertilizers has to be balanced by their costs that strongly depend on price developments on national and international markets. IA models can either adopt exogenous projections for such price developments or, based on general equilibrium and economic growth models, apply endogenous price dynamics.

Trade linkage

A significant share of agricultural products in many regions is either exported or imported. Trade supplements domestic food supply by distributing agricultural products to places of unfavorable conditions for cultivation. Many land-use models base their trade decisions either on historical patterns or on cost minimization without taking the macroeconomic feedbacks into account. In the real world, countries that specialize in agricultural production accumulate revenues from exporting these products that allow them to import manufacturing goods without running a current account deficit. Analogously, trade decisions in the modeled agricultural system have to be embedded into the macroeconomic trade balance.

In a typical IA model with separated land-use and macroeconomic modules, the effect of agricultural trade on the trade balances cannot be investigated. It can be argued that this effect is marginal, since the share of agricultural trade in the overall trade volume is small. However, this does not apply to all regions. Latin America, for example, exhibits

a value share of agricultural exports of around 15 per cent in total exports. A first step in the direction of integrated trade balance accounting is given by an approach that feeds agricultural trade volumes (in monetary terms) into each region's budget constraint. This implies that each dollar of export surplus relaxes the budget constraint and qualifies for an import of another good with the value of one dollar in the same period. Within an intertemporal model this export surplus can be balanced any time by an import of a commodity with a net present value of one dollar. While this integrates agricultural trade in the overall trade balancing, it is still a one-way link. There is no reaction of agricultural trade on the implied changes in the trade balance. The agricultural trade patterns may change when feedbacks are taken into account, but only few IA models have as yet modeled this interface in a way that general equilibrium effects are captured. Moreover, agricultural trade is strongly subject to trade policies. Tariffs and subsidies restrict the amount of trade that otherwise would occur. As IA models typically assess climate policies in the long run, only few of them include the impact of trade barriers, but reference is given to domain-specific models.

IMPLEMENTATION OF LAND-USE IN INTEGRATED ASSESSMENT MODELS

Here we provide an overview of three IA models from the literature with a detailed representation of agriculture and land-use. This is followed by a short description of our own modeling framework which is then applied to a policy case in the following section.

IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) (MNP, 2006; Stehfest et al., 2009; <http://www.pbl.nl/en/themasites/image/>) links agricultural demand and supply for 24 world regions with a range of environmental parameters on a spatial grid with a resolution of 0.5×0.5 degrees. The agricultural sector is disaggregated into seven crop and five livestock groups. The agro-ecological zone (AEZ) concept is applied to determine productivity of crops and rangeland at the grid level (Leemans and van der Born, 1994). The land-use module in IMAGE is initialized with land cover information from satellite data and official statistics, and then calibrated according to FAO for the period 1970–2000 (Klein Goldewijk et al., 2007; FAO, 2007). A computable general equilibrium (CGE) model is used to simulate agricultural demand, production and trade for the future (Eickhout et al., 2009; Verburg et al., 2009). Future productivity changes are prescribed as exogenous trends. Land-use is allocated at the grid level with a rule-based approach (Alcamo et al., 1998a). If agricultural demand can not be met, the land-use module is solved by expanding cropland and rangeland into natural vegetation. The related CO₂ emissions are taken into account based on IPCC figures (IPCC, 2006). Bioenergy is not in direct competition with food or forest production, as it is only produced on abandoned cropland and rangeland. Livestock can be produced either in pastoral systems or in mixed systems, which are distinguished by different feed efficiencies. Calculation of methane and nitrous oxide emissions from enteric fermentation and animal waste management is derived from total feed requirements and feed composition

as well as external estimates (Bouwman et al., 2005; Steinfeld et al., 2006; IPCC, 2006). Mitigation policies and efficiency improvements in crop and livestock will reduce emissions per unit of output in future scenarios in IMAGE.

GCAM

The Global Change Assessment Model (GCAM) (previously named MiniCAM) is a long-term, integrated assessment model (Wise et al., 2009; <http://www.globalchange.umd.edu/models/MiniCAM.pdf>). It combines a model of the global economy, energy systems and agriculture and land-use with representations of terrestrial and ocean carbon cycles. Moreover, it contains a set of gas-cycle, climate and ice-melt models, which are also coupled. The GCAM energy–economy–land-use framework is a recursive-dynamic partial equilibrium model. External drivers include population size, age and gender, and labor productivity. They drive potential GDP in 14 world regions. GCAM is used to assess potential future developments over the period 1990 to 2095 in 15-year time steps. Supply and demand for agriculture, forestry, energy and land are balanced through a price-based market-clearing mechanism. These market outcomes are also explicitly linked to the use of unmanaged ecosystems and the terrestrial carbon cycle. In addition to sectoral economic output and prices and land-use, GCAM also models emissions of 15 greenhouse gases and aerosols as well as stocks of terrestrial carbon. GCAM allocates land to competing uses and provides the rental rate on land, carbon stocks and flows associated with land-use. Land is allocated between alternative uses based on expected profitability. Future changes in crop productivity are taken as exogenous inputs (Bruinsma, 2003). Changes in the area of land under cultivation in GCAM depend on the land rental rate. Thus increased demands for land result in higher rental rates and expansion into unmanaged ecosystems. Historical land-use and production are mapped to the 14 GCAM regions based on global maps of historical cropland, rangeland and potential vegetation (Klein Goldewijk, 2001, Klein Goldewijk et al., 2007, Ramankutty and Foley, 1999). GCAM distinguishes nine crop groups and five livestock groups. Livestock feed can be produced in pastoral or mixed systems, according to Bouwman et al. (2005). Carbon is distributed in GCAM among 15 reservoir types: unmanaged forests, other unmanaged land, managed forests, nine food and fiber crop types, bioenergy crops; pasture; and non-arable land. Stocks of above- and below-ground terrestrial carbon are calculated in GCAM based on IPCC (2001) and Monfreda et al. (2009). Land-use changes (e.g. converting forest land to cropland) induce a change in carbon fluxes resulting in additional CO₂ emissions.

IGSM

The Integrated Global System Model (IGSM) couples sub-models of the natural earth system to a model of the human component (Sokolov et al., 2005; Melillo et al., 2009; http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt124.pdf). It contains a model of human activity and emissions; an atmospheric dynamics, physics and chemistry model; an ocean model with carbon cycle and sea-ice sub-models; and a linked set of coupled land models. Time steps used in the various sub-models range from 10 minutes to 5 years, reflecting differences in the characteristic processes simulated by IGSM. The

Emission Prediction and Policy Analysis (EPPA) model is a recursive-dynamic, multi-regional computable general equilibrium (CGE) model with 16 world regions (Paltsev et al., 2005). It is built on the GTAP database (Dimaranan and McDougall, 2002) and additional data for the emissions of greenhouse gases, aerosols and other atmospheric pollutants. EPPA generates projections for GDP, energy use and sectoral output as well as emissions of GHGs and other air pollutants from combustion of carbon-based fuels, industrial processes, waste handling and agricultural activities. Uncertainty analysis is applied to estimates of population growth and rates of technological change. IGSM supports analysis of a variety of mitigation policies and costs, and changes in international trade. The agriculture sector in EPPA can be disaggregated into crops, livestock and forestry, with an explicit treatment of land-used in each sector. Global land-related processes in IGSM are represented by a dynamically linked set of terrestrial biogeophysical and biogeochemical sub-models. The treatment of land systems guarantees conservation of water and energy between these sub-models. Land-use change can be analyzed at different spatial grids. IGSM employs three coupled sub-models to represent terrestrial water, energy and ecosystem processes. The Community Land Model (CLM) calculates the global, terrestrial water and energy balances (Bonan et al., 2002). The Terrestrial Ecosystems Model (TEM) simulates CO₂ fluxes and the storage of carbon and nitrogen in vegetation and soils (Melillo et al., 1993; Xiao et al., 1997, 1998; Felzer et al., 2004). The Natural Emissions Model (NEM) simulates fluxes of CH₄ and N₂O (Liu, 1996; Prinn et al., 1999).

REMIND–MAgPIE–LPJmL

The integrated assessment modeling framework REMIND–MAgPIE–LPJmL, partly developed by the authors, is composed of three independent models—the Lund–Potsdam–Jena dynamic global vegetation and hydrology model with managed Land (LPJmL) (Bondeau et al., 2007), the global land-use optimization Model of Agriculture and its Impact on the Environment (MAgPIE) (Lotze-Campen et al., 2008; Lotze-Campen et al., 2010; Popp et al., 2010a, b), and the Regionalized Energy-economy-climate Model on Innovation and technological Development (REMIND) (Leimbach et al., 2010).

LPJmL simulates biophysical and biogeochemical processes of natural vegetation as well as productivity and yield of the most important crops at the global scale. Natural vegetation is represented by a limited number of plant functional types, while agriculture is represented by 11 crop functional types, including cellulosic bioenergy crops. LPJmL simulates the transient changes in carbon and water cycles due to land-use and climate change, the specific phenology and seasonal CO₂ fluxes of agriculture-dominated areas, and the production of crops and grazing land at 0.5×0.5 degree spatial resolution (i.e. approx. 50 by 50 km). The special feature of the model is the dynamic, fully process-based interaction between carbon and water cycles, including agricultural crops and soils.

MAgPIE is a global land-use allocation model which is soft-coupled to LPJmL. It takes regional economic conditions as well as spatially explicit data on potential crop yields, land and water constraints into account and derives specific land-use patterns, yields and total costs of agricultural production for each grid cell. The objective function of the land-use model is to minimize total cost of production for a given amount of

agricultural demand. Regional food demand is defined for an exogenously given population and income growth in ten food categories (cereals, rice, vegetable oils, pulses, roots and tubers, sugar, ruminant meat, non-ruminant meat and milk) based on regional diets (FAOSTAT, 2008). Food and feed energy for the ten demand categories can be produced by 20 cropping activities and three livestock activities. Feed for livestock is produced as a mixture of grain, green fodder and pasture at fixed proportions. Cropland, pastureland and irrigation water are fixed inputs in limited supply in each grid cell. The optimization approach assigns an implicit economic value to scarce resources, which is an interesting feature for non-marketed inputs, e.g. irrigation water in many regions. Variable inputs of production are labor, chemicals and other capital, which are assumed to be in unlimited supply to the agricultural sector at a given price.

The model can endogenously decide to acquire yield-increasing technological change at additional cost, which is a distinctive feature compared to other land-use and agricultural sector models. For future projections the model works with time steps of ten years in a recursive dynamic mode. Optionally, additional land from the non-agricultural area can be converted into cropland at additional cost. Carbon content for different land-use activities and crop yields is supplied by LPJmL for each grid cell. CO₂ emissions from land-use change occur if the carbon content of the previous land-use activity exceeds the carbon content of the new land-use activity. MAGPIE operates on a regular geographic grid with a resolution of 0.5×0.5 degrees. For more efficient computation, the original number of about 60 000 grid cells is reduced by a clustering algorithm. Each cell of the geographic grid is assigned to one of ten economic world regions, which are initially characterized by data for the year 1995 on population (CIESIN et al., 2000), gross domestic product (GDP) (World Bank, 2001), food demand (FAOSTAT, 2008), average production costs for different production activities (McDougall et al., 1998) and current self-sufficiency ratios for food (FAOSTAT, 2008).

The REMIND model is an integrative framework that embeds a detailed energy system module into a macroeconomic growth module and integrates a climate system module that computes the effect of GHG emissions. The REMIND model is completely hard-linked and solves the three integrated modules, simultaneously considering all interactions in an intertemporal optimization procedure. The application presented below uses a global single-region version, while the model can also be split into 11 world regions. The energy system module comprises a detailed description of energy carriers and conversion technologies. Techno-economic characteristics and the system of balance equations that set up the energy system are constraints in the welfare maximization problem of the macroeconomy module. The energy system demands investments from the capital market that are allocated endogenously among a portfolio of more than 50 alternative energy conversion technologies. A number of transformation technologies can be combined with carbon capturing and sequestration. This applies to fossil-fueled power stations but also to the production of transport fuels and hydrogen based on fossil fuels and biomass.

Compared to other IA models, the REMIND–MAGPIE–LPJmL framework has a number of methodological improvements: REMIND explicitly links a detailed energy system module with an advanced representation of macroeconomic investment dynamics and trade; MAGPIE integrates a representation of endogenous technological change into a spatially explicit agricultural sector model; and LPJmL provides fully process-based

interactions between carbon, water and agricultural production. These different features are combined in a flexible soft-coupling approach.

CLIMATE POLICY APPLICATIONS

We present an illustrative climate policy study that is based on an application of the REMIND–MAGPIE–LPJmL framework presented in Popp et al. (2011). Within the assessment, the global bioenergy demand and related impacts are calculated under a climate policy that aims to limit the rise in global mean temperature.

Since joint optimization of complex models is limited in terms of computational efficiency and solvability, a soft-link approach (Bauer et al., 2008) is applied to run the integrated model. Figure 10.3 shows the data exchange. In a pre-processing step, MAGPIE is informed by simulation data from LPJmL. The soft-coupled MAGPIE and REMIND models are solved in isolation and information flows between them ensure convergence to an equilibrium that is approached in an iterative process (meta-optimization).

The chain starts with REMIND (R) calculating a global bioenergy demand scenario (B) in the energy system up to 2100, based on given biomass cost curves (S_B).

$$B = R(S_B)$$

These data are delivered to MAGPIE (M), which computes new cost curves for biomass for the biomass scenario obtained from REMIND.

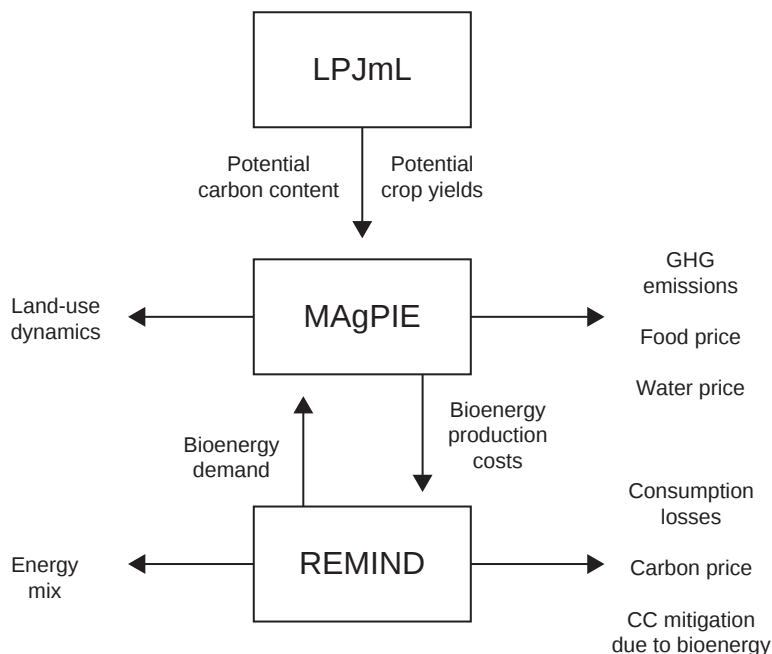


Figure 10.3 Integrated assessment framework

$$S_b = M(B)$$

This iterative process is repeated until equilibrium is established: that is, no more change in bioenergy demand (derived by REMIND) and costs (derived by MAgPIE) occurs.

We apply our land-use–climate–energy–economy model framework under different scenarios to assess the potential contribution of bioenergy to climate change mitigation, including its side effects. A reference scenario portrays a possible future without climate change mitigation. Bioenergy demand is low and no forests are conserved, that is, all suitable land is available for cropland expansion. Here, suitable land is defined by the global agro-ecological assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Velthuizen et al., 2007). This scenario serves as a point of reference for the assessment of cropland expansion and associated CO₂ emissions from land-use change, but also N₂O emissions from agricultural intensification and impacts on food and water prices under bioenergy scenarios. GHG emissions associated with the cultivation of dedicated bioenergy crops will be contrasted with CO₂ emission reductions from the energy sector due to the use of bioenergy. In this way, the actual contribution of bioenergy for low stabilization of GHG concentration in the atmosphere is evaluated.

In the climate change mitigation scenarios, global bioenergy demand is calculated by REMIND under climate policies that limit the increase of global mean temperature to 2 °C compared with the pre-industrial level. In tropical developing countries, bioenergy production will lead to an additional pressure to convert intact and frontier forests into cropland. These forests represent areas of high value for carbon (Houghton, 2003) and for biodiversity (Barlow et al., 2007), so there is a potentially perverse impact when forest carbon is released for the purpose of bioenergy production (Wise et al., 2009; Persson and Azar, 2010). Therefore we distinguish between a scenario with and a scenario without forest conservation. In the forest conservation scenario the land pool available for cropland expansion is constrained by the share of intact and frontier forests (Bryant et al., 1997; Greenpeace International, 2005) for each grid cell such that 100 per cent of forest is conserved.

The simulation results indicate that in the scenario without forest conservation, bioenergy demand increases steadily up to 281 EJ in 2095 with a demand of 91 EJ in 2055. However, forest exclusion for the purpose of biodiversity conservation and climate change mitigation reduces the availability of cost-efficient biomass for energy production significantly in the medium term (55 EJ in 2055). In the long term the maximum amount of bioenergy supplied is 243 EJ in 2095.

In the reference scenario, total cropland increases from 1487 million ha in 2015 to 1881 million ha in 2095. In the bioenergy scenario without forest conservation, global cropland area increases up to 1943 million ha in 2095. Around 12 per cent of this amount is used for bioenergy crop cultivation. Forest conservation reduces the amount of total cropland area by 408 million ha in 2095 compared to the bioenergy scenario without forest conservation.

The main alternative options of meeting the demand for food and bioenergy products in the agricultural system are represented by (a) intensification and yield increases on currently used agricultural land and (b) land expansion into currently non-agricultural

areas. Here, we present rates for additional yield increases due to the application of bioenergy. Because of restrictions of land availability for agricultural expansion, higher rates for yield increases can be found in the scenario with forest conservation (additional 0.5 percentage points per year until 2055 and 0.3 percentage points per year until 2095) compared to the scenario without forest conservation (additional 0.3 percentage points per year until 2055 and 0.1 percentage points per year until 2095).

Additional GHG emissions associated with land-use change due to the use of dedicated bioenergy crops sum up globally to 0.9 GtCO₂ in 2055 and 0.2 GtCO₂ in 2095. But if forest is conserved, additional GHG emissions from land-use change associated with the application of dedicated bioenergy crops can be avoided. Here, to obtain CO₂ emissions that refer to the application of dedicated bioenergy crops only and to calculate the contribution of bioenergy to climate change mitigation (see below), we compare the outcome of the mitigation scenario with the outcome of a reference scenario that also considers forest conservation.

Moreover, our simulation results reveal that additional N₂O emissions from the application of industrial N fertilizers rise strongly over time, up to 1.7 GtCO₂e and 1.6 GtCO₂e in 2095 in the scenario with forest conservation and the scenario without forest conservation, respectively.

Until 2095 bioenergy use contributes to climate change mitigation by reducing 1546 Gt of CO₂ emissions in the energy system in the bioenergy scenario without forest conservation. This is somewhat lower in the 'forest conservation' scenario – 1338 GtCO₂. In both scenarios emission reduction is due to an accelerated increase of biomass use and a shift of biomass use towards technologies that operate in combination with carbon capturing and sequestration.

In the scenario without forest conservation, the actual contribution of bioenergy to climate change mitigation, that is, CO₂ emission reductions from the energy sector due to bioenergy that are not offset by N₂O emissions from agricultural intensification, and CO₂ emissions from land-use change associated with the cultivation of dedicated bioenergy crops, increases over time. Lowest values of nearly 0 per cent can be found in 2015 and highest values of around 37 per cent in 2095. Accumulated over the time horizon until 2095, 5.6 per cent of CO₂ emissions reductions due to bioenergy use are offset by CO₂ and N₂O emissions from land-use change associated with the cultivation of dedicated bioenergy crops. Within the scenario with forest conservation, the actual contribution of bioenergy shows similar values despite the land restriction (see Table 10.1). Only 4.1 per cent of cumulative CO₂ emissions reductions from the energy sector due to bioenergy use are nullified in this scenario by additional CO₂ and N₂O emissions.

The global aggregated food price index, that is, the average of all crop and livestock activities weighted with their average share in total food demand, is not affected if bioenergy demand is taken into account and all suitable land is available for land expansion. But in the scenario with forest conservation the food price index rises by 17 per cent in 2095 compared to the reference scenario.

In the scenario without forest conservation, the global water price index, that is, changes in shadow prices for irrigation water relative to the reference scenario, increases slightly by 2 per cent in 2095. The forest conservation scenario increases the shadow price for water by 14 per cent in 2055 and by 7 per cent in 2095 because bioenergy cropland competes directly for irrigation water with other agricultural activities.

Table 10.1 Results from IA climate policy application

	No forest conservation		Forest conservation	
	2055	2095	2055	2095
Bioenergy supply [EJ]	91.8	281.3	55.8	243.0
Cropland area [mio ha]	1804.7	1943.5	1523.2	1534.8
Additional annual yield increases (relative to reference scenario) [%]	0.3	0.1	0.5	0.3
N ₂ O emissions (additional to reference scenario) [Gt CO ₂ e]	0.5	1.7	0.3	1.6
CO ₂ emissions (additional to reference scenario) [Gt CO ₂ e]	0.9	0.2	0.0	0.0
Emission reduction in energy system (relative to reference scenario) [Gt CO ₂ e]	11.1	40.7	7.6	37.7
Real contribution of bioenergy to total emission reduction [%]	11.0	37.4	12.0	34.7
Global food price index (change relative to reference scenario) [%]	-0.9	0.1	20.8	17.3
Global shadow price of irrigation water (change relative to reference scenario) [%]	3.7	2.3	13.8	6.8
Carbon prices [\$t CO ₂]	65.5	105.5	67.4	126.3
Consumption losses (relative to reference scenario) [%]	1.0	0.19	1.0	0.23

Source: Own calculations.

Table 10.1 provides a summary of results from the illustrative integrated assessment study. Such results can be used to substantiate mitigation policy decision making.

CONCLUSIONS

In the previous sections it was shown that the agricultural and land-use system plays an important role in IA models. State-of-the-art IA models integrate land-use modules in a way that allows for covering GHG emissions as well as mitigation options related to land-use and land-use change. However, research is needed to further improve the modeling of the land-use system and its interaction with the other components of an IA model. Next steps can be summarized as follows:

1. IA models that include an agricultural and land-use module take interactions with the climate system only in a reduced form into account. More complex interactions between different factors should be considered. In particular, a more elaborated hydrologic component has to be implemented to capture the explicit links between water use in agriculture and other sectors as well as water availability. This includes the modeling of climate-related changes in rainfall intensity and implied risks of soil erosion and salinization.

2. Some IA models project emissions of non-CO₂ gases in the agricultural sector. Still, mitigation options and potentials in crop and livestock production have been covered by only a few IA models, while hardly any IA model evaluates the mitigation potential of these gases beyond the marginal abatement cost curve approach.
3. Productivity changes are crucial for land-use activities. Most IA models, however, treat them exogenously. Alternative approaches that endogenize technological change in the land-use system are needed.
4. While land expansion into forest and related CO₂ emissions are captured by a number of IA models, complex policy options for avoiding deforestation have still to be introduced.
5. The investigation of bioenergy expansion needs to be linked to the investigation of implied environmental impacts (e.g. water availability, biodiversity, other ecosystem services) as well as social impacts (e.g. rural employment).
6. Emissions that result from an increase in global population and a change in food composition can play a major role in the future. Modeling the relationship between food composition, per capita income levels and cultural characteristics is needed.
7. Investments into agricultural machinery, other assets and also in R&D have to be modeled so that general equilibrium effects are captured, including endogenous price dynamics. This can be implemented by linking the agricultural model to a general equilibrium and economic growth model. In an intermediate step, agents of the agricultural system can be modeled with more sophisticated capabilities of expectation formation.
8. Trade flows in the agricultural sector have to be embedded into the macroeconomic trade balance. While this may shift the macroeconomic trade pattern, especially for less-developed regions, the agricultural trade patterns may change as well when feedbacks are explicitly taken into account.

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11 The role of growth and trade in agricultural adaptation to environmental change

John Reilly

INTRODUCTION

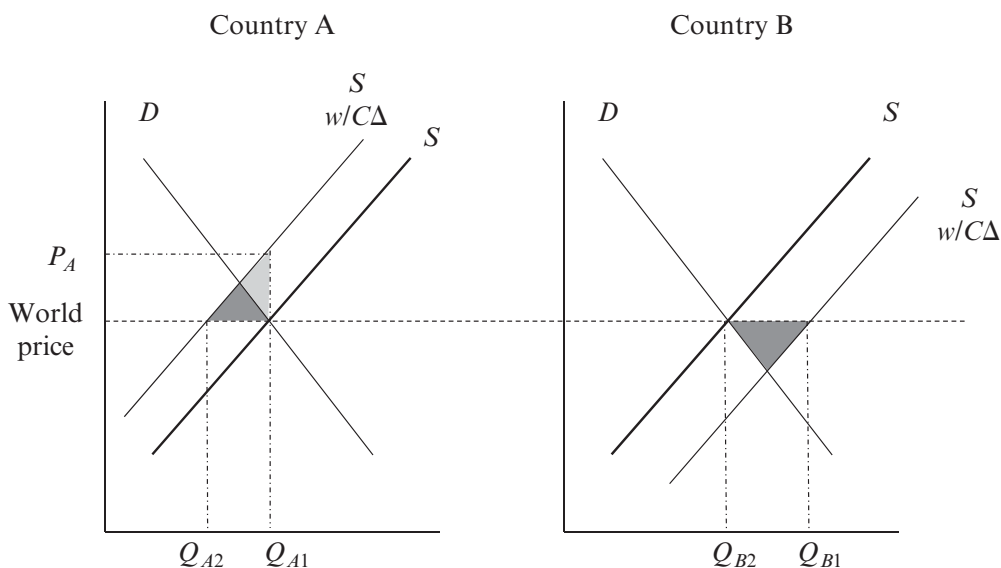
International trade is important for agriculture, and agriculture is changing rapidly to meet the demands of a growing and likely wealthier world population even as potentially new demands are placed on agricultural resources. The interventions of governments in their domestic agriculture sectors distort trade in significant ways; however, these interventions generally fail to insulate countries and regions from world market forces. For many problems, the importance of trade would generally support the use of partial equilibrium analysis where a ‘small-country’ assumption would mean that prices were set in global markets and changes within the country would have little effect on them. However, the phenomenon of human-induced climate change and the broad forces of economic growth are necessarily global, and so agricultural markets in all regions are affected simultaneously. As a result, if environmental effects on agriculture are negative in many places, agricultural prices will rise and farmers whose yields are affected negatively may at least look to the positive side of higher prices for their product. Conversely, if climate change has generally positive effects on yields in many regions, the result will be lower prices for agricultural commodities that, while good for food consumers, will reduce revenue for farmers. Similarly, what adaptation measures make economic sense to undertake in a region will depend on changes in global agricultural markets – if prices rise, it may justify more expensive adaptation measures such as adding irrigation in regions that have become more drought-prone. On the other hand, if prices fall, an otherwise marginal area may become uneconomic for farming, with no hope of recouping investment in expensive adaptation measures such as irrigation, even though such a measure might restore or even increase yields. Finally, as research moves from understanding the potential impacts of climate and environmental change on agriculture to identifying adaptation strategies, it is important to move from a single-minded focus on climate because successful strategies need to be adapted to broader economic changes, of which climate change is only one force.

Issues of trade, environmental change and growth, and adaptation of agriculture to these forces are the focus of this chapter. The next section lays out the simple trade story in graphical form and relates this to early work that has focused on agricultural trade and climate change. Then a section describes important global forces that are likely to drive agricultural adaptation in the future, and a following section identifies some of the key research issues and uncertainties in estimates of response to climate change.

TRADE AND CLIMATE CHANGE

As Reilly and Hohmann (1993) and Reilly et al. (1994) showed, the net economic impact on a country through agricultural impacts of climate change can often be the reverse of the yield effect if countries are large importers or exporters of food, because the economic impact is dominated by what happens to the global market price. They found that a rise in global prices, reflecting an average negative effect on yields globally, benefited agricultural exporting regions in many cases, with harm or gain being measured as the sum of consumer and producer surplus changes even though their yields were negatively affected, while a fall in global prices often harmed agricultural exporting regions even though their yields may have improved. Similarly, an importing region whose agriculture is adversely affected by climate may nonetheless benefit from climate change if global prices fall, or be hurt if prices rise even though agricultural productivity in the region improves. Hence partial equilibrium approaches that take into account only the change in climate and its impact on yields or land values and not the effect on global prices can be misleading, not only in magnitude but in the sign of impact.

The basic trade story can be shown graphically as in Figure 11.1, which shows Country A where climate change has a negative effect on yields shifting the supply curve to the left; for simplicity it is assumed that the world price for agricultural commodities with climate change is unchanged. This could be, for example, a tropical country where



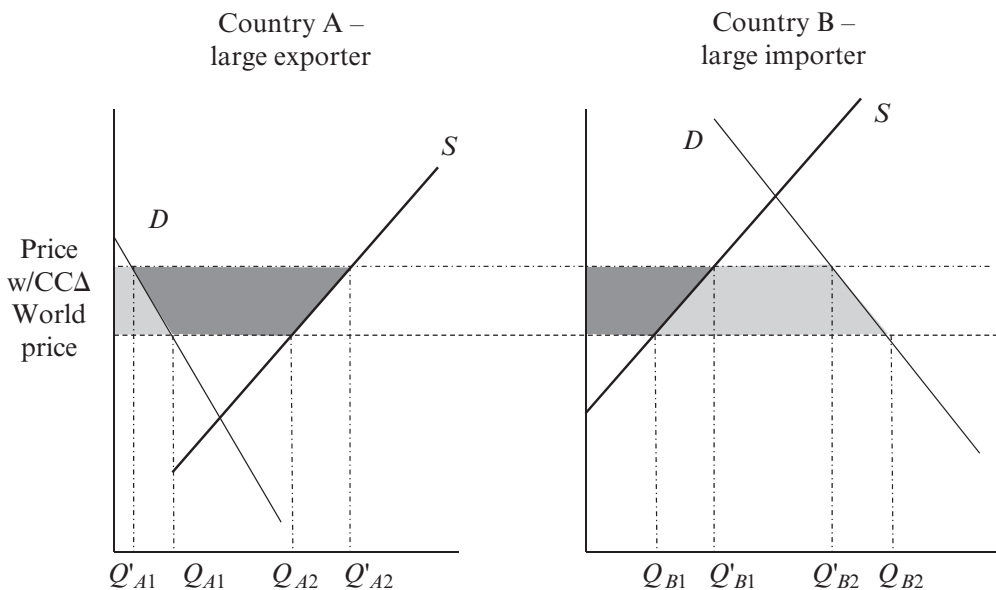
Note: Two countries (A and B) with food demands (D) and supplies before climate change (S) and after climate change ($S w/C\Delta$) and a world price given by the world market. As shown before climate change there is no incentive for either to trade but if climate change causes Country A (e.g. a tropical country) to have yield losses and Country B (e.g. a northern temperate country) to have yield gains, then A would cut production from level Q_{A1} to Q_{A2} and import and B would expand production from Q_{B1} to Q_{B2} and export, here assuming that climate change leaves the world price unchanged.

Figure 11.1 Role of trade in climate impact on agricultural-based countries

most literature suggests even modest climate change could have negative effects. Again, for simplicity, the figure is drawn with the assumption that prior to climate change the country supplied all of its agricultural output with its domestic industry. With open trade and the conditions that go along with the small-country assumption (that Country A's demand on world markets has a negligible effect on the world price), the quantity produced would fall from Q_{A1} to Q_{A2} , but demand would remain unchanged at Q_{A1} , implying net imports of $Q_{A1} - Q_{A2}$.

The supply curve with climate change is drawn with the intention of representing how farmers would adapt given the yield effect from climate they observed at different hypothetical prices for their output. Continuing to exhibit the traditional upward slope, a story consistent with this shift, for example, is that drought probably leads to reduced average yields (or yields in those parts of the country so affected) but that higher prices would make further adaptations economically viable. For example, we might suppose that at the price P_A it would be worthwhile to irrigate significant areas affected by drought and, as shown here, the price of P_A would just restore the output level to Q_{A1} . Higher prices would bring forth more adaptation – perhaps areas not affected by more severe drought would be irrigated as well, thereby eliminating yield losses that had always been associated with occasional drought in these areas, or new areas not previously cultivated would be converted to cropland. Without trade, production and consumption would be determined by the intersection of the demand curve and the new supply curve (S_w/CA), and the level of production would fall by less, resulting in a rise of domestic prices. While these points are not explicitly designated on the chart, they occur where vertical and horizontal lines from the intersection of demand and supply meet the quantity and price axis. With trade the country is worse off with climate change than without because of its deteriorating climate, but the gains from having trade are the light green triangle. Suppose the country tried to restore production to its pre-climate change level: the effective supply price would need to then rise to P_A , restoring production to Q_{A1} , but to dispose of this much output domestically would require a domestic price equal to the pre-climate impact price (the unchanged world price). The actual resource cost of this extra production is the green gain-from-trade area plus the light red triangle area. Such a policy would thus eliminate the gains from trade (the green triangle) and incur additional losses associated with producing agricultural goods with unnecessarily costly adaptation measures.

Country B is also shown, where climate change increases yields as illustrated, with a rightward shift in the supply curve. Here the country would gain from climate change even without trade, again the market equilibrium in this case is the intersection of the demand curve with the supply curve after climate change. In the absence of trade, this would result in lower domestic prices benefiting consumers, but also lower production costs for a given level of output for producers because of the improved natural climate conditions. Whether producers gain or lose (lower production costs and lower prices work in opposite directions), production expansion depends on demand and supply elasticities. Because demand for food is generally considered to be inelastic and the supply of agricultural products relatively elastic, an increase in production is expected to lead to a relatively sharper drop in prices resulting in a net loss to agriculture, and a restriction in production raises prices leading to a net gain. Because in competitive markets industries should earn a normal rate of return, such net losses or gains are expected to be



Note: Country A is a large exporter and Country B a large importer prior to climate change. Quantities demanded before (Q_{A1} , Q_{B1}) and after ($Q'A_1$, $Q'B_1$) climate change and quantities supplied before (Q_{A2} , Q_{B2}) and after ($Q'A_2$, $Q'B_2$) climate change.

Figure 11.2 Impact of climate change on supply of food

capitalized into the land price. With trade and the assumed unchanging world price, all of the gains would go to producers in country B, as they were able to expand production and export a quantity $Q_{B1} - Q_{B2}$. The reverse was true in Country A, where access to trade avoided consumer losses from the domestic effects of climate change, but aggravated producer losses.

The Ricardian approach of Mendelsohn et al. (1994) makes use of the observation that changes in resource rents associated with climate change are capitalized into land values, but no account is taken of changing commodity prices, resulting in a method that is an accurate indicator of economic impact only under the circumstances shown in Figure 11.1, where world price for commodities does not change and the country remains open to trade. Hence consumers are unaffected and all impacts fall on producers, being captured in changes in land rents. As a method of econometric estimation where land prices vary with climate for a given price, the approach can, in principle, reveal the relationship between climate and agriculture given a fixed price, but in projecting forward economic impacts the results can be misleading. To see this, consider possibilities where the world price changes and countries start from a position of being a large exporter or importer relative to domestic consumption. Figure 11.2 illustrates such a case where now Country A is a large net exporter and Country B is a large net importer. For simplicity, we suppose that climate change leaves the agricultural productivity of these two countries unchanged; there is no shift in their aggregate supply, but changes elsewhere in the world lead to a rise in the world price for agricultural commodities.

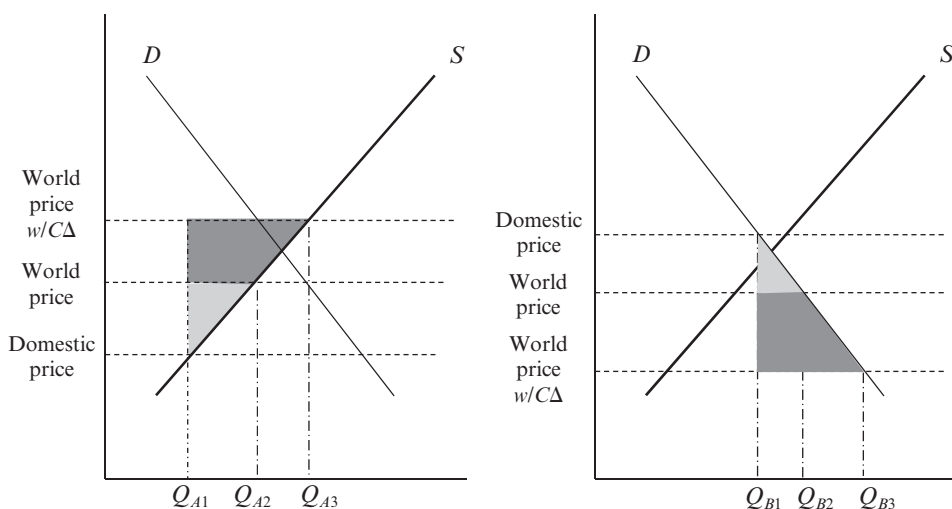
In this example, there are no direct climate effects on supply in aggregate in either country, perhaps a balance of gains in some parts of the country and negative effects elsewhere, but Country A gains from climate change while Country B is a net loser because of the transmission through trade of global effects. In Country A, consumer loss from higher prices is represented by the pink area, the producers gain is the green plus the pink area, and so the net effect on the country is the producer surplus gain less the consumer loss equal to the green area. In contrast, in Country B, pictured as a large net importer, the producer gains are just the green area, the consumer losses is the green plus pink area, and the net loss is the consumer loss less the producer gain equal to the pink area. One could obviously extend these graphs and consider cases where the world price changes and there are direct negative or positive effects on agricultural productivity in the country that either offset gains or losses, or increase them. It is also clear that export–import status could change as a result of climate change. An exporting region negatively affected by climate change could become an importer, especially if climate change had little effect on world prices or actually reduced them. Similarly, an importing region could become an exporter if domestic effects were benign or beneficial, and global effects of climate were strongly negative. Reilly et al. (1994) plotted the relationship between export–import status and net effect on countries for some example climate scenarios, and while that work is now quite dated, it shows the general result that exporters tended to gain if climate change raised world prices while importers lost. But this was not universally the case; there were exceptions, as we might expect given this graphical analysis.

Rosenzweig and Parry (1994) showed further that differential ability to adapt could further enhance trade effects. In that work, they found considerable ability to adapt in Northern temperate regions and less adaptation potential in tropical regions, which led to the counter-intuitive result that in a global model with trade, agricultural production fell more in tropical regions with adaptation than without. This early result indicates how economically appropriate adaptations depend on the global effects of climate change and responses to them, and is illustrated in Figure 11.1 where the possibility of Country A attempting to maintain production levels as its agricultural productivity was damaged by climate change, even though world prices were unchanged. However, as noted, trade can change who benefits and loses within a country. In a situation where trade further reduces domestic agricultural production, the economic benefits associated with trade assume that displaced farmers and agricultural workers can find work in other sectors of the economy. Many tropical regions include countries where at present a significant share of the economy and labor force is in agriculture. If these regions follow a development path similar to other developed countries, it is likely that the share of agriculture in the economy and labor employed in agriculture will fall even if the countries remain large agricultural producers and exporters. Climate change that disadvantaged agriculture in these countries would then accelerate this movement out of agriculture, and any problems that existed in absorbing this labor pool into other sectors of the economy would be exacerbated.

As noted in the introduction to the chapter, government intervention in agriculture is a near universal phenomenon and the above figures were drawn as if markets were operating without distortions. Even with significant distortions, markets generally operate, only they do not necessarily have the desired outcome of minimizing costs of producing a given level of output. Intervention in agriculture has been driven by different forces in

Country A – maintains lower than world prices,
world price rises

Country B – maintains higher than world
prices, world price falls



Note: Country A maintains a domestic price below the world price; Country B maintains a domestic price above the world price, assuming neutral effects on these countries of climate change but either a world price increase or decrease due to impacts of climate change in other regions. Quantity supplied (Country A) and quantity demanded (Country B) given the domestic policy (Q_{A1} , Q_{B1}) and for the world price without (Q_{A2} , Q_{B2}) and with (Q_{A3} , Q_{B3}) climate change.

Figure 11.3 Climate change impacts under agricultural price distortions

developed and developing countries. In the developed countries, much of the intervention in agriculture has historically been designed to maintain agriculture production and to support the income of farmers. Justification for these programs has often been in the name of price stability, with government agencies buying up commodities when prices were low and then selling them when prices were high. However, with a constituency of farmers, prices were more often seen as too low, leading governments to try to raise prices beyond their long-run market level and, as a result, surplus stocks of commodities developed. In developing countries, the historical reason for intervention in agriculture was more often to maintain lower food prices for the poor in urban areas. Also, industrialization was often equated with development, and trade and tariff policy that made import of industrial goods more expensive to support domestic industry also had the effect of restricting import of inputs needed in agriculture. Hence agriculture in developing countries was often squeezed by high input prices and low domestic prices for commodities, aggravated to the extent that developed countries dumped surplus commodities into world markets. Over the past 15 to 20 years the push for reduced trade barriers in agriculture under the World Trade Organization has reduced some of the distorting practices, but reducing these barriers has been a slow process and so distortions remain.

The effect of distortions, represented as pricing policy that seeks to have the domestic price differ from the world price, is represented in Figure 11.3, showing how climate change might affect domestic economies with these price policies in place. Here Country

A attempts to maintain a domestic price that is below the world price. This results in added cost to the economy because it undermines domestic agricultural production, leading to greater imports and higher consumption than would otherwise be the case. This in turn results in a net loss to the economy represented by the small pink triangle. The diagram is drawn supposing that the effect of climate change on world agriculture is to raise the world price; as in Figure 11.2, for simplicity's sake we assume that climate change leaves domestic agricultural production unchanged. The result, if the country maintains the absolute pricing policy, is to increase the loss by the amount of the darker pink trapezoid.

These losses are known as 'deadweight loss' in economics. The figure illustrates a feature of changes that aggravate such losses: even though the price rise from climate change is drawn to be about the same as the domestic price was below the initial world price, the additional deadweight loss is three times the original loss from the policy. It aggravates the losses associated with the original pricing by increasing the loss per unit production on the previous level of production, the rectangular portion of the trapezoidal area, and adds the triangular portion of the trapezoid where domestic production could have expanded further to reduce imports of more expensive foreign goods, resulting in, as drawn, the country becoming a net exporter under climate change if it did not pursue the pricing policy. A couple of issues are worth noting:

1. To the extent that there are distributional benefits of the domestic pricing policy, these are not represented in the figure. Pricing policy helps poorer consumers afford food, but if it is a general pricing policy it also applies to the relatively wealthy consumers and thus may not be as efficient as more focused distribution policies. If a country proceeded to eliminate domestic pricing policy, it would need to replace that with other policies aimed at meeting distributional objectives.
2. It may not be possible for the country to maintain the pricing policy; it requires purchase of agricultural goods at the world price to be sold at the low domestic price. Government subsidies would be needed to make this happen. A rising world price would thus have government budget implications that may be untenable. Then, to the extent that food prices were achieving a distributional goal, that goal would be threatened.

In Figure 11.3, Country B is shown facing the opposite situation of Country A. It is a country that maintains a domestic price above the world price to support agricultural production and farm income at the expense of consumers. Here it is also assumed that the impact of climate change on the world price is to lower it, the opposite of the situation pictured in the Country A panel, and that climate has no net effect on domestic agricultural supply. The initial cost of this market-distorting policy is again the light pink triangle. Here the lower world price with climate change increases the deadweight loss by the light red trapezoid. The situations of both countries were drawn where the climate impact on world markets worsened the existing distortion. Reversing the climate impact in both cases would reduce the pre-existing distortion, possibly eliminating it. As in previous diagrams, it is assumed that these countries are small relative to the global market so that the change in imports or exports by the country has a negligible effect on the world price.

It is unlikely that these price floors and ceilings would actually remain unchanged. As already noted, a price ceiling, which holds prices below the world price, would create budget pressure if the world price increased significantly. On the other hand, a price floor that became non-binding because of world price rise may lead agricultural producer interests to push for revisions to the price policy so that it remained binding. Lewandrowski and Brazee (1993) discuss specific types of policy interventions and how they might interact with climate change.

To summarize this section: (1) considering only the direct impacts of climate on agriculture in a region provides an incomplete estimate of the economic impact on the country or region, (2) the economic impact may be of opposite sign of the direct impact, (3) the economic efficacy of adaptation approaches depends on what happens to world prices, (4) domestic agricultural policies can attempt to isolate production and consumption from climate change or the trade effects of changes abroad, but those policies will create economic costs that could be avoided, (5) pre-existing distortions may be aggravated or reduced by climate change, although such changes would probably create pressure (on government budgets or by constituents of the policies) to revise the distorting policies.

BROADER FORCES SHAPING AGRICULTURE

The simple diagrams of the previous section are useful devices to show the separate effects of climate change (or other shocks to domestic or global prices). Farmers and the agricultural sector will need to adapt to market prices, and whether the cause is climate or something else will matter little. On the other hand, adaptation to the direct effects of climate change at the farm level will be specifically related to the nature of climate change. If drought is an issue, then adoption of more drought-resistant crops, irrigation or other cropping practices that make better use of limited water might be indicated. If increased pests are a problem, then practices that control the specific pests are obvious adaptation measures to consider. Whether these make economic sense or not will depend on market prices, as they are affected via climate effects on all producing areas and by other forces. The forces, other than climate change, that will be important are:

- meeting the world's growing and changing demand for food as population and income increase;
- adapting to other environmental issues such as tropospheric ozone, aerosol haze and soil degradation;
- reducing agriculture's effects on other environmental problems such as reduced soil erosion and runoff of nutrients into streams, lakes and coastal areas;
- other competition for land and water to meet energy, recreation and urbanization needs;
- continued competitive pressures from increasingly globalized agricultural markets and the 'industrialization' of agriculture; and
- changes in technology

Reilly (2002) reports on a dialogue with agricultural stakeholders who identified many of these forces. Given that climate change effects on global agriculture could be either

positive or negative, and among these forces are effects that could lead to higher prices as well as those that could reduce prices, adding climate considerations could either reinforce price expectations or offset them.

Here only the briefest review of these issues is possible. Population growth is slowing and many projections have growth stabilizing in most countries between 2050 and 2100. In some areas such as Europe, Russia and Japan, population has actually begun declining, and China's population will begin to decline soon if current birth rates are maintained. As a result the global population, currently nearing 7 billion, may increase to no more than between 9 and 10 billion (United Nations, 2009). While this is a substantial absolute increase, agricultural production will not need to respond to the near exponential growth in population of the last century. However, income growth in poorer countries has led to adoption of diets with more meat as in wealthier countries, and this is expected to continue (CAST, 1999). The trend toward more meat in the average diet will put greater pressure on agricultural resources because the production of meat, especially beef, is relatively inefficient in terms of area of land needed to produce a given number of calories or pounds of usable protein. By one estimate the number of people fed in a year per hectare ranges from 22 for potatoes and 19 for rice down to 1 and 2 people, respectively, for beef and lamb. The same study estimates that a hectare of land used to produce soybeans produces 356 pounds of usable protein and rice 261 pounds, while meat production in general produces 45 pounds, and beef 20 pounds of usable protein per hectare of land (Gold, 2004). The range of estimates and calculation methods for such simple statistics vary substantially and are highly debated, in part because such statistics are often used to advocate for diets that have less meat. Here, the point is simply that this trend toward more meat, which is in fact occurring, will create greater demand for land, other things being equal. However, these efficiencies and land resource requirements are not a given as there are many different production practices with different resource implications and opportunities for efficiency improvements (CAST, 1999).

Environmental effects on agriculture from factors other than climate change may have negative consequences for yields. Soil degradation from irrigation with poor drainage, overgrazing and wind and water erosion is a substantial problem. FAO (2010) provides online national soil degradation maps showing degradation in categories ranging from none, light, moderate, severe and very severe; however, it is difficult to identify the effects on yields. For example, much of the US Corn Belt is identified as severely degraded but because these soils are so deep, productivity remains high. (For a discussion, see Lal, 2001; Weibe, 2003). Conventional air pollutants can also have damaging effects on productivity. Estimates suggest yield losses may be on the order of 5 per cent (Adams et al., 1986; Westenbarger and Frisvold, 1994, 1995), but these could increase if precursor emissions of ozone are not stringently controlled (Reilly et al., 2007), potentially counteracting the positive direct effects of CO₂ (Tubiello et al., 2007).

While environmental change may affect agriculture, agricultural production practices can also have detrimental environmental consequences through soil erosion, which delivers sediment and nutrients to lakes, rivers, estuaries and coastal areas, and contamination of groundwater through leaching of agricultural chemicals. In addition, groundwater mining may ultimately restrict irrigation either because of draw-down of water, concerns about subsidence or its effects on ecosystems. Some examples of how these issues may

interact with climate change include Chen et al.'s (2001) study of the Edward's Aquifer, Chen and McCarl's (2001) examination of the potential effects on pesticide use and Abler et al.'s (2002) study of nutrient and sediment impacts on Chesapeake Bay.

Food, fiber and forest product markets have traditionally been the markets that create extensive demand for land. Urban and industrial uses of land account for a small percentage of actual land area in most countries, and so would not appear to be a strong competitive force on agricultural land prices except in the urban fringe where maintaining green space is of local concern. Recreation demand, if it is realized through public ownership of land and restrictions on its use or as private property ownership (e.g. Antoine et al., 2008); biofuels and biomass energy (e.g. Gurgel et al., 2007); or forest carbon sequestration (e.g. Sohngen and Mendelsohn, 1998; Gurgel et al., 2010) could place substantial competing demands on land for conventional agricultural uses.

The industrialization of agriculture is a broad concept that refers to the institutional structure in which farming is practiced, and how risks and rewards are shared. Rather than individual farmers growing products, taking them to the market and selling for whatever price they fetch, industrialization refers to a structure in which large central firms with a global reach contract or hire people to manage production, with likely increasing specialization of production in regions best suited for particular crops. As agriculture moves in this direction, international competitiveness is highlighted. Drivers of this trend are the demand for uniform products and assured continuous supply throughout the year, the 'risk-pooling' inherent in such an organizational structure where crop failure in some regions is offset by good harvests in others, the ability of large organizations to bring in the investment and financing at levels needed and the reshaping of how risks (and rewards) are shared between the land holder and the industrial enterprise. This process has extended fairly far in the USA, especially in fruit, vegetable and livestock markets, but less so in grains production, probably because US commodity programs have had some effect on farm size.

Finally, technological change has in the past been a major source of productivity improvement in agriculture, measured either as total factor productivity or in terms of yield growth for key crops (Ruttan, 2002), but debate continues as to whether we are near limits in yield growth (Reilly and Fuglie, 1998). However, focusing on yield growth can miss other sources of total factor productivity growth in agriculture. For example, Carolan et al. (2007) and Laser et al. (2009) describe bioprocessing refineries that could produce multiple products, including feedgrain-equivalent livestock feed, ethanol and other biochemicals from a general biomass stock; that is, material from any plant that would grow under changing conditions. Such a process would greatly increase the economic productivity of land by producing valuable feedgrain-equivalent products that use the entire plant rather than just the grain, increasing the amount of product refined even though yields on specific crops did not increase at all. Using a wide range of biomass feedstocks with different climatic tolerances would increase the climatic range suitable for providing bioprocessing feedstocks in relation to traditional feedgrains. The tropics might become major feedgrain product (or livestock product) and fuel suppliers with corn and soybean production in the USA disappearing, and that land used instead to produce other higher-valued grains and crops for direct human consumption. It has also been hard to separately identify whether yield growth is an exogenous phenomenon driven by advances or limits in basic science and how much is response to prices, either

through input substitution or through endogenous technical change response. On the one hand, many agricultural economic models that treat yield and area explicitly find very little evidence that yield responds to prices, suggesting that supply response is mainly through acreage increase. On the other hand, it is commonly assumed that agricultural demand is relatively inelastic and supply elastic. Following short-run increases in commodity prices, we often see a huge supply response within a few years that leads to gluts of commodities beyond any area expansion. This evidence seems in conflict with inelastic yield response to price, or at least evidence that there is supply responsiveness somewhere in the system. The source of the difference may be short-run annual responses, which one would expect to be negligible, and longer-run responses of five to ten years that are difficult to estimate.

RESEARCH CHALLENGES AND NEW DIRECTIONS

Much of the early research on impacts of climate change on agriculture, especially from the perspective of economics, was directed toward asking the question: what are the aggregate economic effects of climate change on agriculture? The implicit, if not explicit, goal of much of this work was contributing to a global cost–benefit calculation: for a mitigation policy, do the avoided damages, of which agriculture was thought to be among the most climate-sensitive sectors, justify the mitigation costs? Among the earliest of such cost–benefit assessments were Nordhaus (1991) and Cline (1992), with later contributions and a review by Tol (2005) citing further studies by Pearce et al. (1996), Mendelsohn et al. (1998) and Nordhaus and Boyer (2000). The most recent contribution is that of Nordhaus (2010), comparing an optimal cost–benefit solution to the 2 °C target of Copenhagen and the actual proposed commitments of countries. Agricultural damages are an important, if uncertain, component of the damage function in all of these studies. Damage assessments are also used to evaluate the social cost of carbon – essentially the current marginal damage associated with emissions – and these have relevance for policy setting (Pearce, 2003). While developing such estimates is problematic, requires strong assumptions and is subject to considerable uncertainty (see, e.g. Stern et al., 2006), such estimates may be an important component in regulatory settings (for example, US Government, Interagency Working Group on Social Cost of Carbon, 2010).

For this type of use it is appropriate that assessment of climate damages to agriculture consider adaptation to climate that is likely to occur, and include estimates of the cost of adaptation. An early debate in the literature was the extent to which adaptation was considered in economic cost estimates. Mendelsohn et al. (1994) argued that their cross-sectional statistical approach, which they termed a Ricardian rent approach because it estimates the changed rents to land associated with climate, better estimated adaptation. That can be contrasted with the crop model assessment approach (e.g. Adams et al., 1990; Rosenzweig and Parry, 1994), which used crop models, often showing results both with and without adaptation, where some farm-level adaptations were evaluated in the crop model, and costly adaptations evaluated as an economic supply response. Some later statistical work (Deschenes and Greenstone, 2007; Lobell and Field, 2007) has used time-series data, and hence has estimated the impact of unexpected weather rather than impacts of long-run changes in climate, which, in principle, are expected. They argue that

these are an upper bound for damage estimates. Another limit is that none of the statistical work effectively incorporates the CO₂ fertilization effect.

More recent work has focused on multiple environmental impacts within a framework of a dynamically changing agricultural system driven by changing population, economic growth and new demands for land resources including biofuels and recreation demand. Reilly et al. (2007) considered ozone damage, CO₂ fertilization and climate change, finding the signature of ozone and climate effects to differ. They found ozone damage to be more severe in northern temperate regions, conveying a trade benefit to exporting tropical regions that is the opposite of the typical climate signature that suggests northern temperate regions will gain or suffer less loss from climate change, thereby conferring a trade advantage on these regions in terms of trade loss to tropical exporters. Melillo et al. (2009) considered the combined effects of greenhouse gas mitigation policy that increased energy costs to agriculture, while also spurring a switch to biofuels that greatly increased resource demand to grow biofuels. These results tended to show that tropical regions were favored for biofuel crops while temperate regions continued to grow food crops. These tendencies were probably reinforced by the fact that warming climate favored traditional food crops in the northern temperate climates while cellulosic biomass crops that can benefit from long growing seasons in the tropics are less vulnerable to rising temperatures. The increased demand for land tended to increase deforestation, contributing to land carbon emissions. Gurgel et al. (2011) considered extending the carbon mitigation measures to protection of forest carbon stocks and to provide incentives for reforestation. While they found that such incentives turned land use into a carbon sink instead of a carbon source, the result was substantial increases in food prices.

In fact, much of the attention in agriculture in recent years has been on biofuels and indirect emissions from land-use change (quite apart from any climate impact) (e.g. Hertel et al., 2010; Tyner et al., 2010). While this work does not directly bear on climate impacts' work, it has indirectly revealed key issues in modeling agricultural markets that strongly affect results when there is a major shock to the system. The focus in these studies is a shock via an increase in biofuels production, but that shock could equally be a large yield shock from climate. Key parameters and structural formulations are those related to: (1) the supply of new cropland or willingness to convert other land to cropland; (2) the ability to intensify production on existing land (e.g. cropland and pastureland) and the degree to which intensification is a response to price; (3) demand for food/crops and (4) the formulation of trade. Hertel (2010) provides an analytical framework that attempts to evaluate the long-run response, arguing that many models represent very short-run behavior. Many assume that yields are completely exogenous and so all response is through intensification or reduction in food demand. Many economic models treat agricultural land as fixed and are simply reallocating it among existing uses, or have a land supply elasticity for cropland that does not explicitly treat where the land is coming from, or how competing demands (for pasture, forest products) are resolved. The work to date also does not effectively integrate water resource effects at a global or even national scale.

The other potential use of agricultural impact analysis is to provide possible adaptation strategies for individual farmers, public and private resource managers and national agricultural ministries, and international agricultural agencies and food relief efforts.

The reduced-form statistical approaches do not, in themselves, provide any specific guidance for adaptation at the farm level, nor, as mentioned earlier, are these sufficient alone to suggest economic benefit or cost to a region unless one assumes world prices are unchanged. The biggest challenge for adaptation is to turn climate forecast information into information that is useful at a time scale relevant to adaptation decisions. Food relief depends on evaluation of conditions as they develop, although if climate risks are believed to intensify food problems, this may indicate that more resources are available in anticipation of deeper or more frequent food crises.

The focus on impacts and adaptation research has turned towards stakeholder involvement, as in the US National Assessment (National Assessment Synthesis Team, 2001). The positive aspect of this trend is to bring potential users of scientific information and the science community together to better understand decisions stakeholders are making that may depend on climate and how climate information could be incorporated. However, with diffuse agricultural stakeholders of many different circumstances and interests, these exercises could at best identify a list of possible adaptation measures that might be helpful to agricultural decision makers in a nation or a large region. Client-based research is, in our evaluation, a natural evolution of 'stakeholder-based' research. The difference is that each client is a very specific stakeholder with a very concrete set of decisions, requiring investment of resources and time in the quest for tailored advice (Reilly and Blanc, 2010).

The key challenge for client-based research is to bring the consideration of climate change into regular decision processes. This involves moving from analysis and evaluation of response to climate change to an analysis of policy formulation on resource management, and decisions people and organizations make where changing climate is factored into the analysis. Farmers face a decision on what to plant each year, recognizing that there are new seed varieties available, new equipment and changed relative prices among crops. As part of that decision, they need to evaluate seasonal projections for weather and climate such as El Niño–Southern Oscillation (ENSO) phenomena, and they need to make some assessment of whether climate conditions have trended sufficiently in some direction to warrant doing something differently. Climate considerations may be embedded in the recommendations of seed producers, equipment suppliers and pest-management consultants. Policy makers face decisions on how to formulate commodity policy, crop insurance, drought and disaster assistance, food stamp and food assistance programs. Climate change is only one consideration in these policy decisions. Similarly, water managers face decisions on how to manage reservoirs and whether improvements or expansion is needed. Increased population and other factors governing demand may be major drivers behind these decisions. One factor to be included is the potential for climate to change availability of water and the demand for it.

A main barrier to the faster evolution of client-based research has probably been a lack of recognition by decision makers at these various levels that climate is actually changing. There now appears to be more of that recognition. The next barrier is to convince decision makers that information on climate that is useful for their decisions and is sufficiently predictive is available. Much of the published literature and major studies on climate impacts has looked at climate change 30, 50 or 100 years in the future. Those time scales have been important for analysts because they have been more confident

that the signal of climate change has risen from the noise. These longer time frames are relevant to national and international climate negotiators asking how much mitigation is needed. These time scales are nearly irrelevant for most major agricultural adaptation decisions. Normal economic discounting simply makes returns that may occur 20 or 30 years in the future not very relevant in a cost–benefit assessment even if the physical life of the project is very long.

SUMMARY

This chapter examined the interactions of climate change and other forces likely to strongly affect agriculture and adaptation. It is important to consider international trade in assessing the economic impacts of climate on agriculture: (1) considering only the direct impacts of climate on agriculture in a region provides an incomplete estimate of the economic impact on the country or region; (2) the economic impact may be of opposite sign of the direct impact; (3) the economic efficacy of adaptation approaches depends on what happens to world prices; (4) domestic agricultural policies can attempt to isolate production and consumption from climate change or the trade effects of changes abroad, but those policies will create economic costs that could be avoided; (5) pre-existing distortions may be aggravated or reduced by climate change, although such changes would probably create pressure (on government budgets or by constituents of the policies) to revise the distorting policies.

Climate impacts will occur against a background of many other important forces of change in agriculture. These include: (1) meeting the world's growing and changing demand for food as population and income increase; (2) adapting to other environmental issues such as tropospheric ozone, aerosol haze and soil degradation; (3) reducing agriculture's effects on other environmental problems such as reduced soil erosion and run-off of nutrients into streams, lakes, and coastal areas; (4) other competition for land and water to meet energy, recreation and urbanization needs; (5) continued competitive pressures from increasingly globalized agricultural markets and the 'industrialization' of agriculture; and (6) changes in technology.

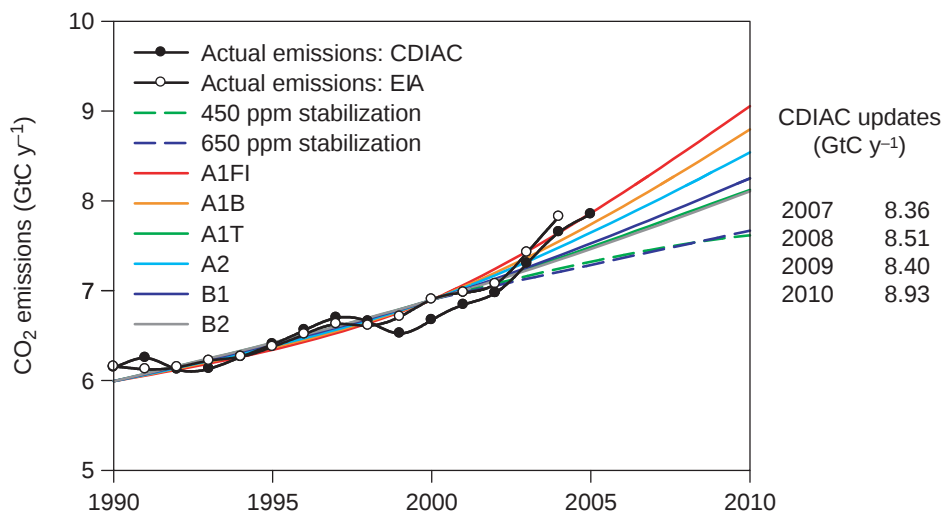
The projection of climate impacts remains highly uncertain because of the inability of climate modeling to produce high-resolution climate forecasts and to consider the range of possible outcomes at time scales relevant to those of adaptation decisions. From a global market's perspective, key parameters and structural formulations that remain uncertain are those related to: (1) the supply of new cropland or willingness to convert other land to cropland; (2) the ability to intensify production on existing land (e.g. cropland and pasture land) and the degree to which intensification is a response to price; (3) demand for food/crops; and (4) the formulation of trade.

Adaptation research must ultimately become part of the regularized process that serves particular clients. A main barrier to the faster evolution of client-based research has probably been a lack of recognition by decision makers at these various levels that climate is actually changing. Now that the evidence of actual change is becoming more widely recognized, the challenge is to develop robust projections of climate and weather that are relevant to decision time frames of 5, 10, or probably at most 20 years.

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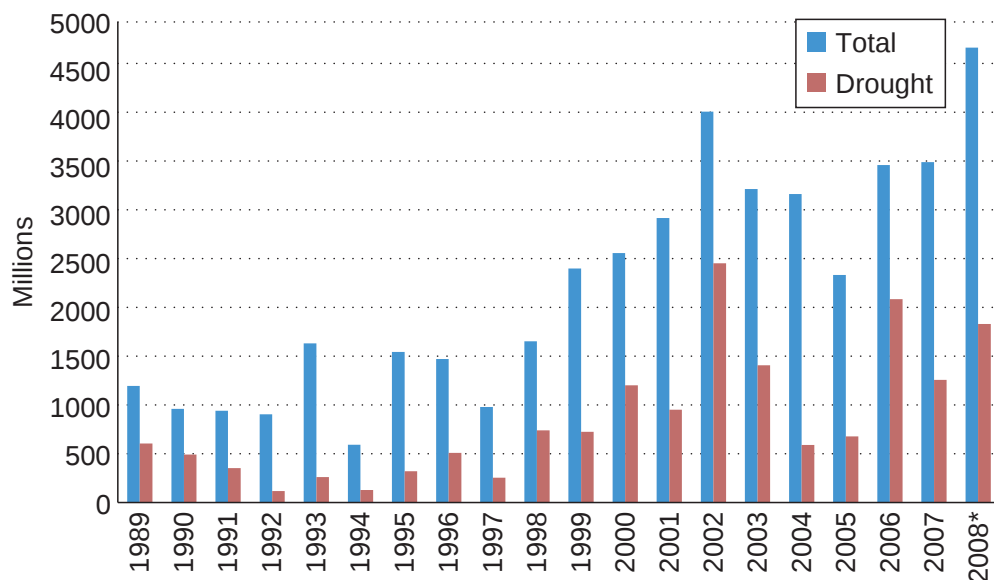
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Note: Actual CO₂ emissions in recent years have exceeded all IPCC projections.

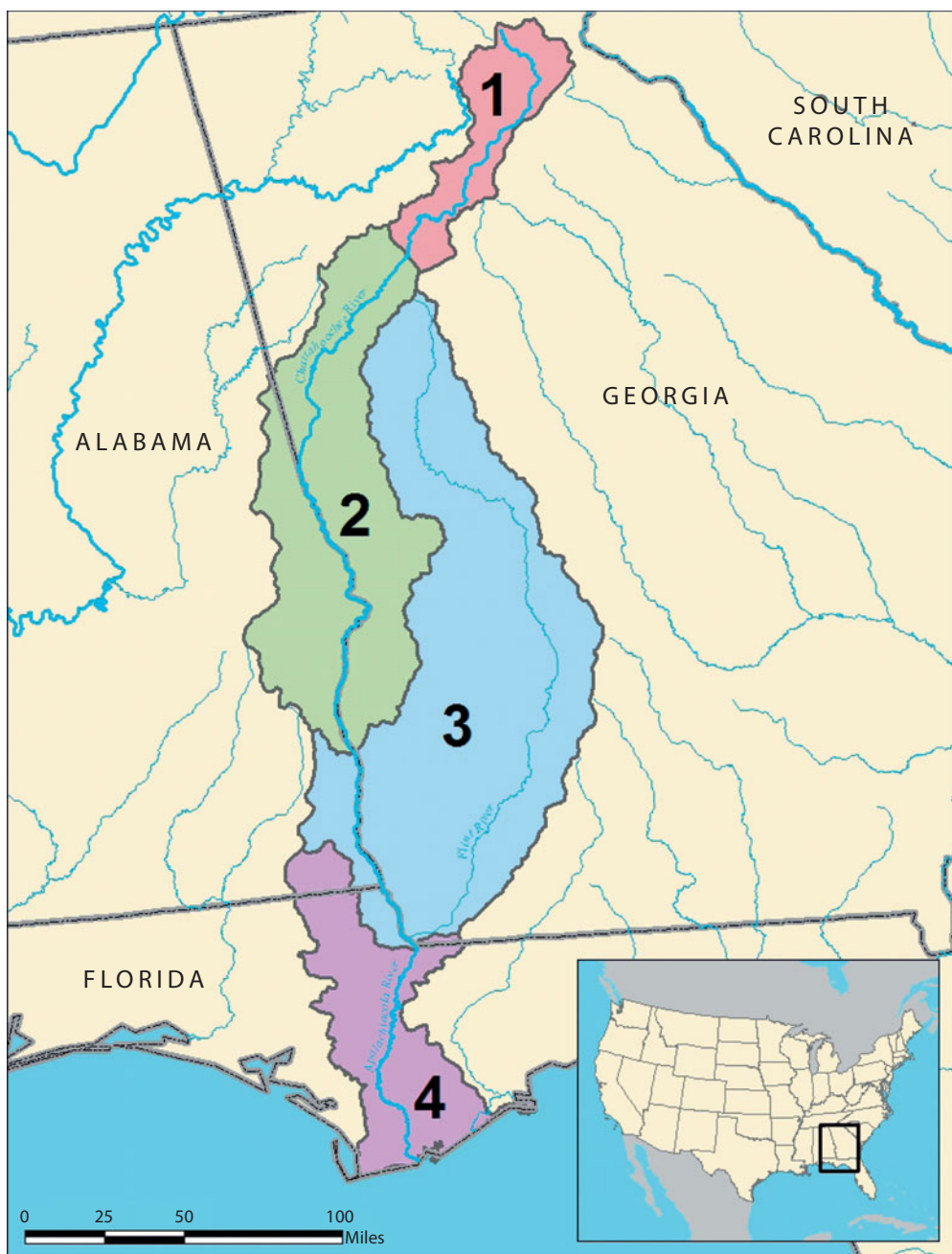
Sources: Raupach et al., modified from Canadell et al. (2007).

Figure 2.1 Different IPCC (2007) scenarios for anticipated changes in global CO₂ emissions (in gigatons per year)



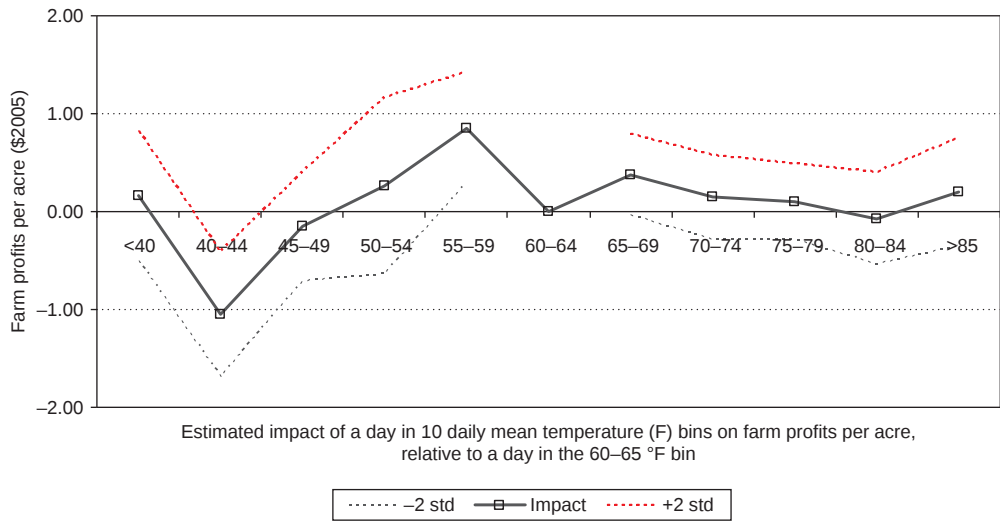
Notes: The red bars are drought-related losses and the blue bars are for all losses. The data for 2008 are not complete.

Figure 5.2 Federal crop insurance indemnity losses (\$) between 1989 and 2008 for the USA



Note: The NIDIS ACF Pilot Project will focus on four sectors in the sub-basins as highlighted: (1) municipal water supplies, (2) energy generation, (3) agriculture, and (4) ecosystems.

Figure 5.3 Sub-basins within the Apalachicola–Chattahoochee–Flint (ACF) River Basin



Notes: The response function is obtained by fitting equation (7.3) and adjusting for state-specific year effects. The response function is normalized with the 60–65 °F category set equal to zero so each estimated coefficient corresponds to the estimated impact of an additional day in bin j on annual farm profits per acre, relative to the annual farm profits associated with a day where the mean temperature is between 60 ° and 65 °F. The figure also plots the 95% confidence interval. See the text for more details.

Figure 7.4 Estimated relationship between farm profits per acre and growing-season daily average temperatures

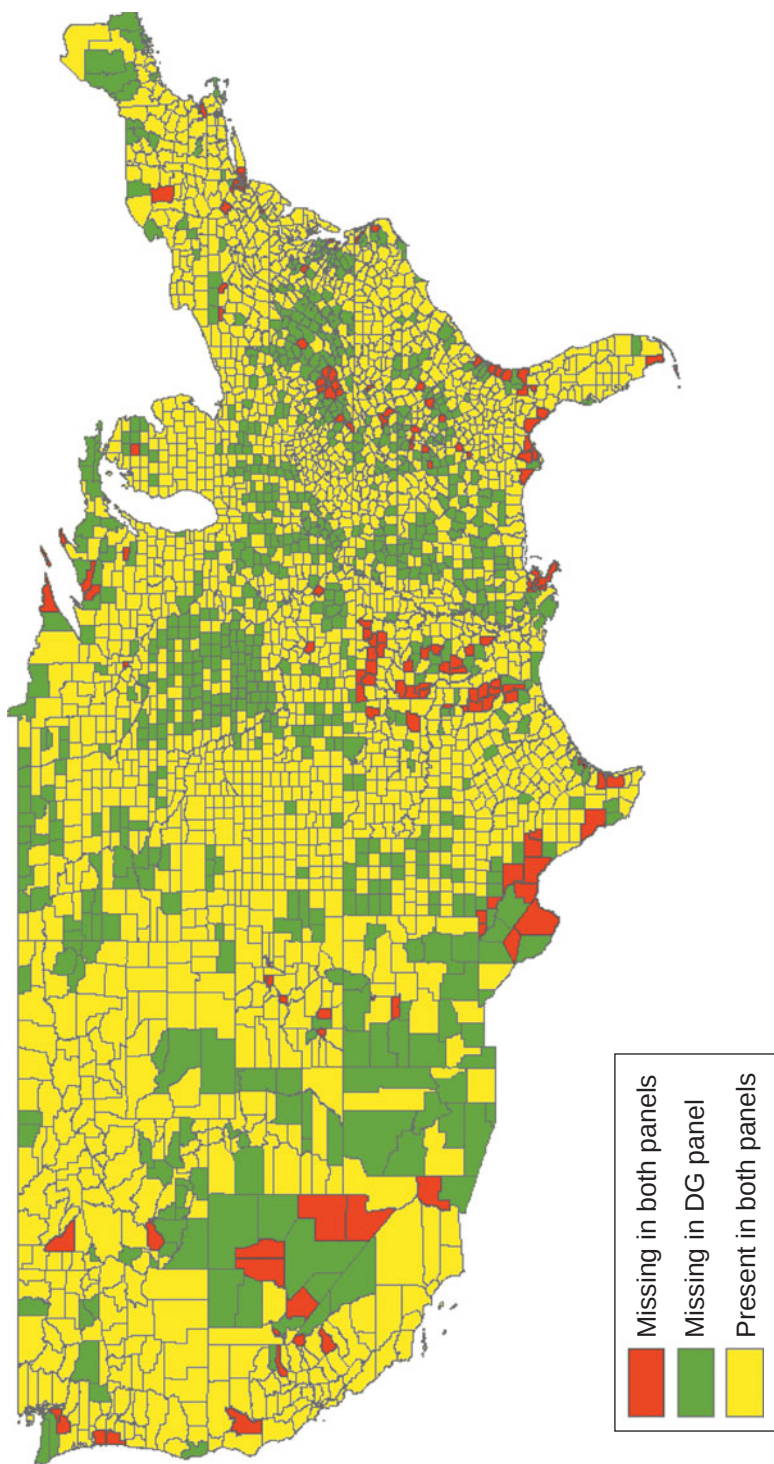


Figure 8.1 Counties covered by DG and expanded panel-data set

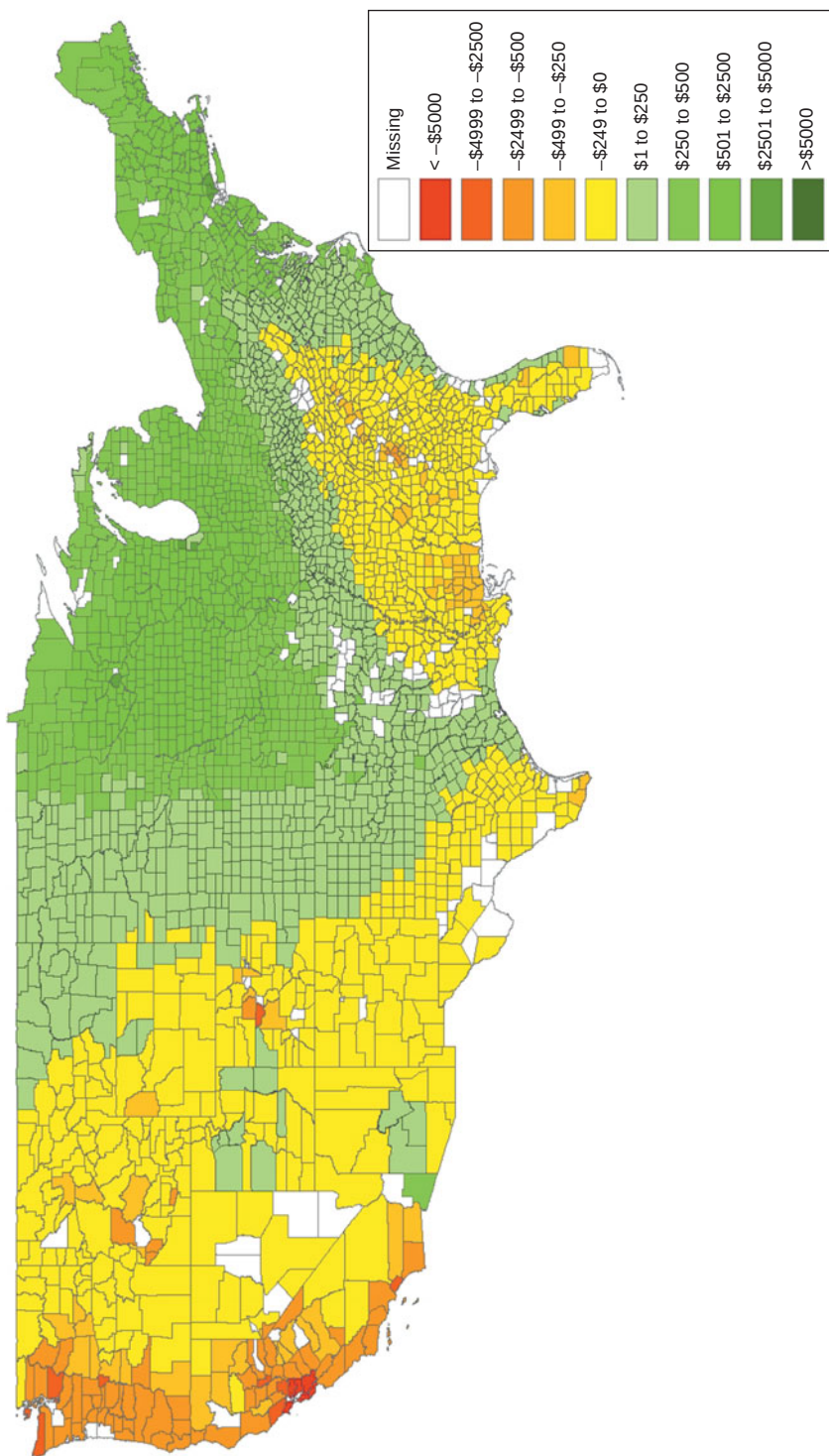


Figure 8.2 The impact of climate change on land value, extended log-linear model, Uniform scenario

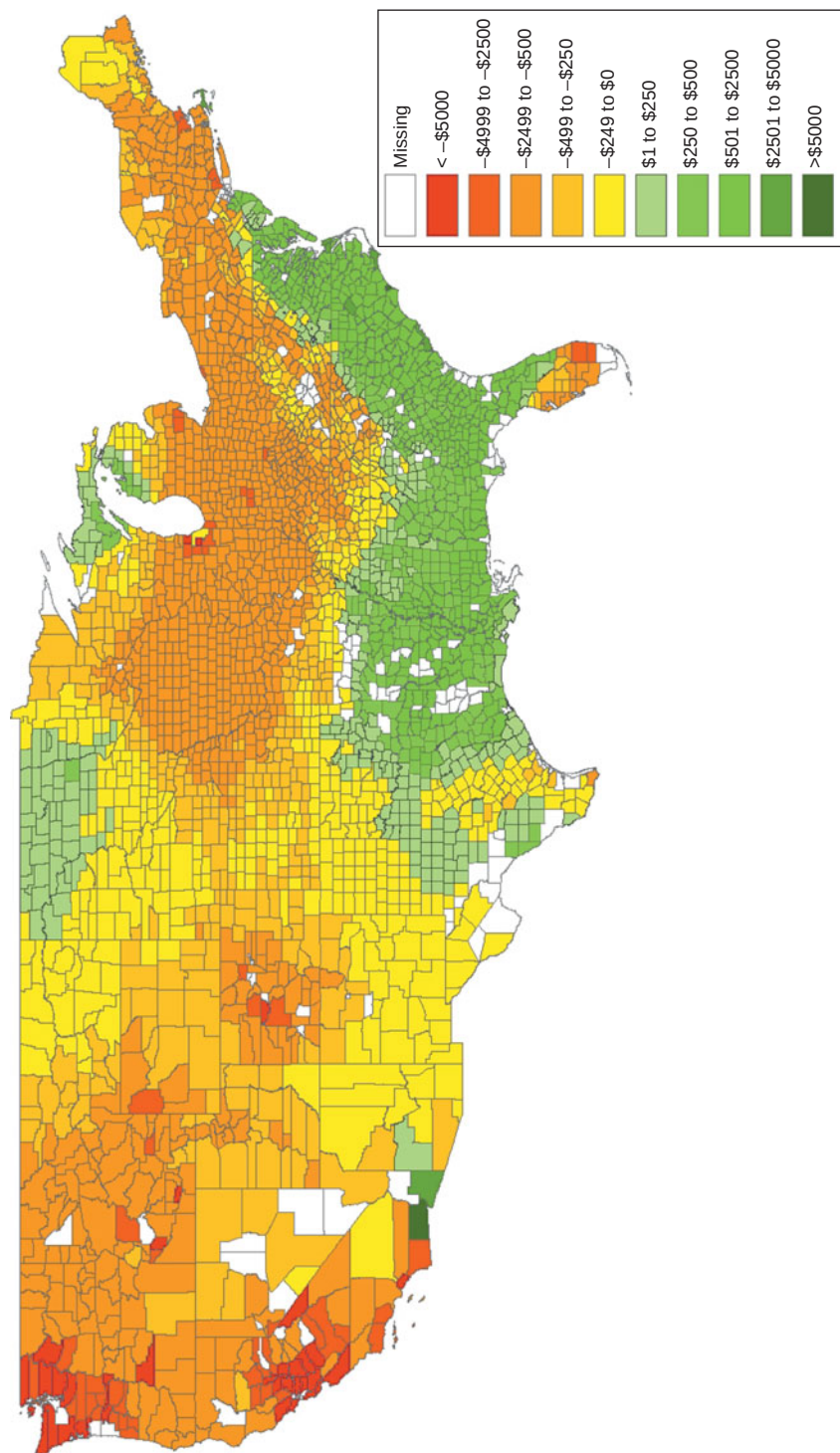


Figure 8.3 The impact of climate change on land value, extended log-linear model, HadCM3 scenario

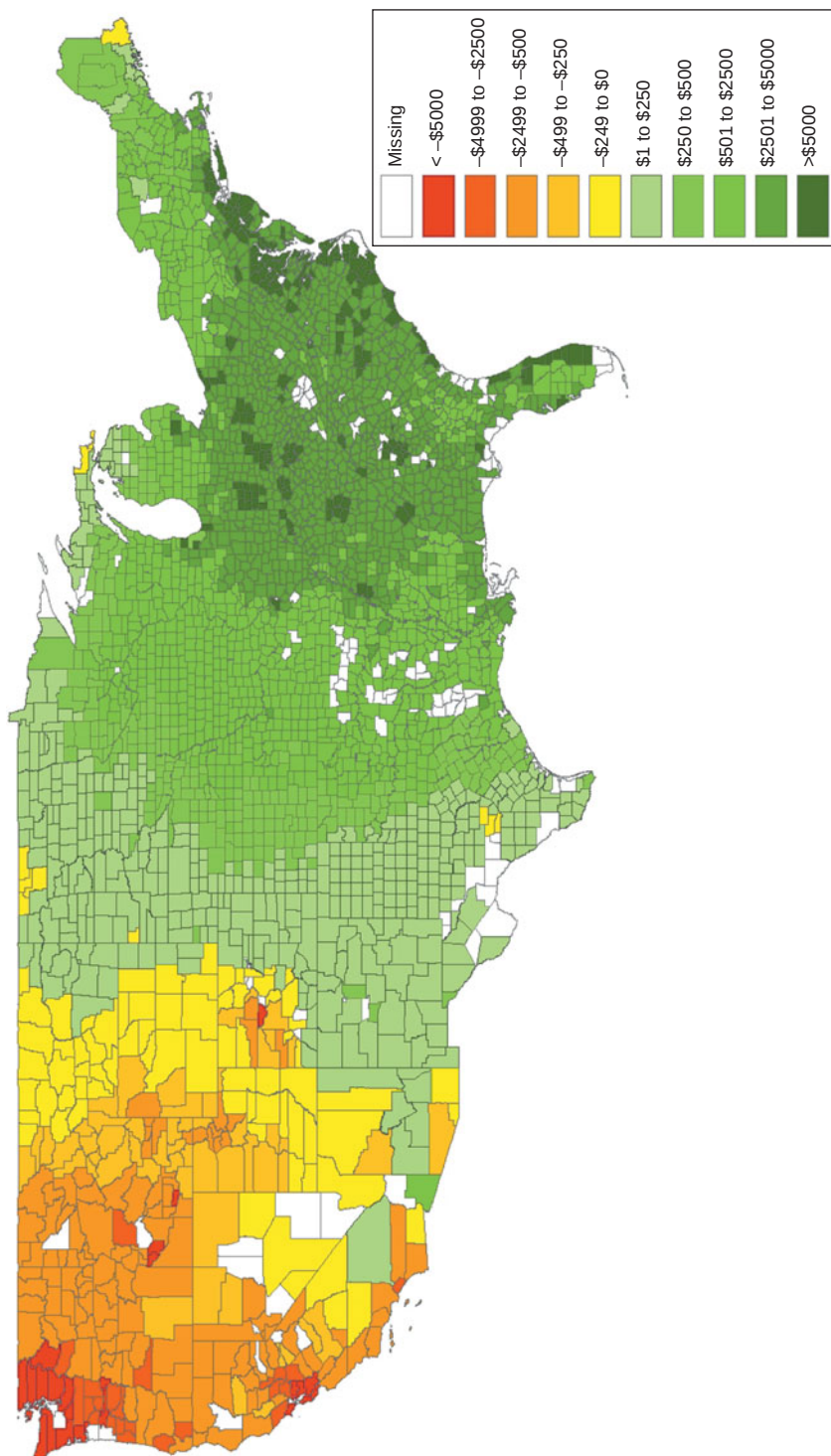


Figure 8.4 The impact of climate change on land value, extended log-linear model, PCM scenario

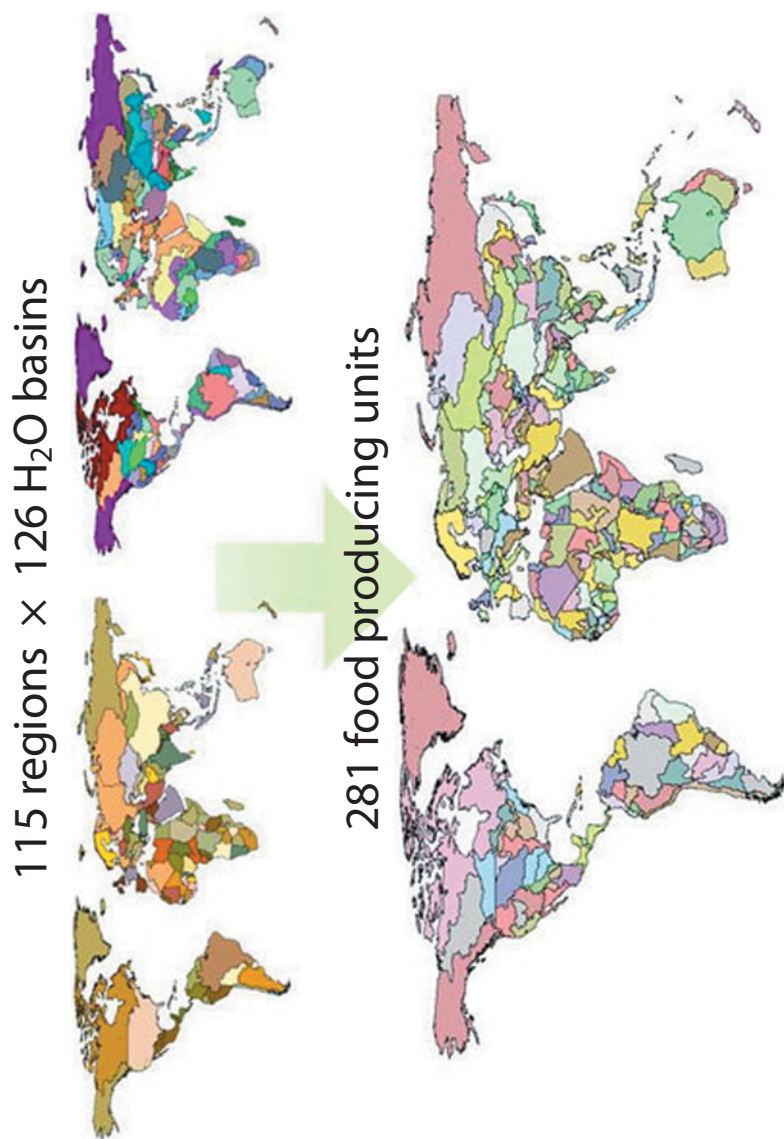
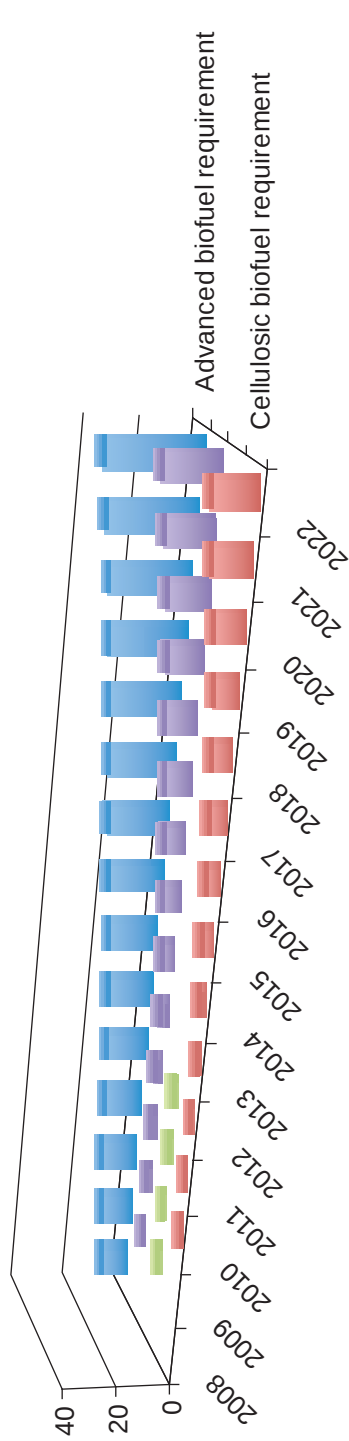
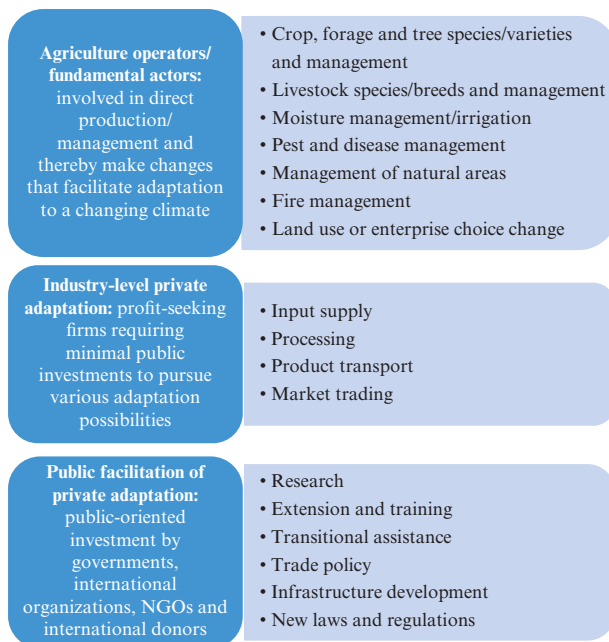


Figure 9.2 Spatial disaggregation of production in IMPACT



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cellulosic biofuel requirement			0.1	0.25	0.5	1	1.75	3	4.25	5.5	7	8.5	10.5	13.5	16
Biomass-based diesel requirement			0.1	0.65	0.8	1									
Advanced biofuel requirement			0.95	1.35	2	2.75	3.75	5.5	7.25	9	11	13	15	18	21
Total renewable fuel requirement	9	11.1	12.95	13.95	15.2	16.55	18.15	21	22.25	24	26	28	30	33	36

Figure 12.3 The volumetric biofuel mandates in the USA



Source: Author's illustration.

Figure 14.1 Possible adaptation actions

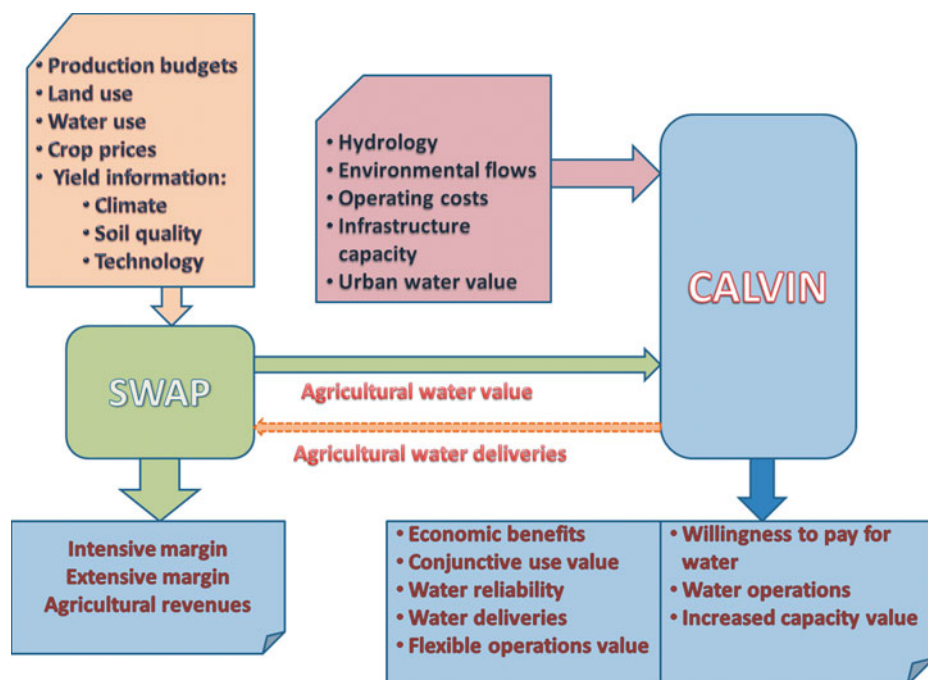


Figure 15.2 SWAP and CALVIN model interaction

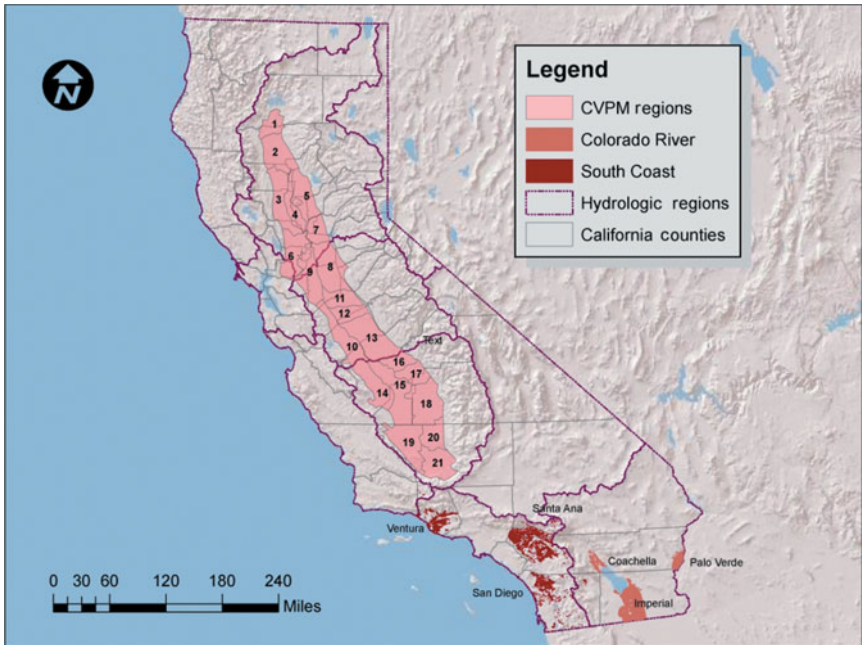
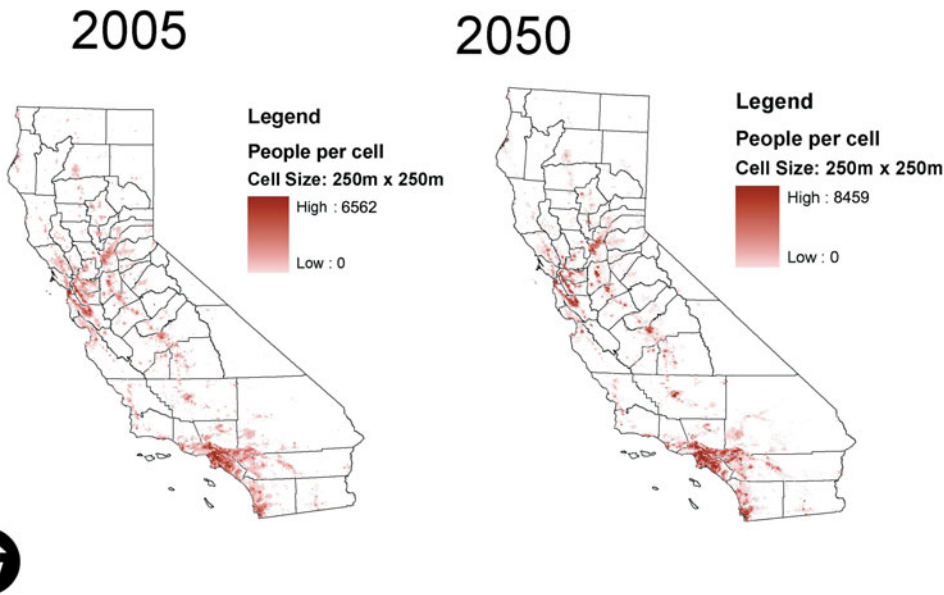
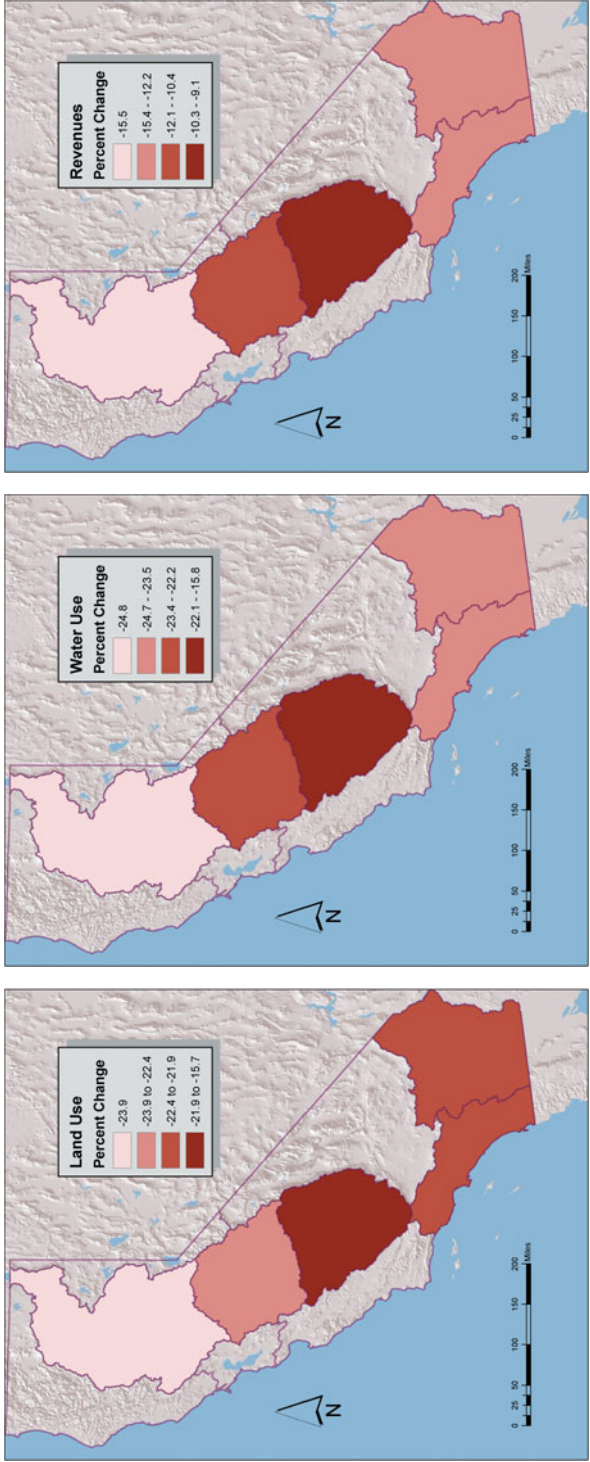


Figure 15.3 SWAP coverage including 21 CVPM regions, and agriculture in Coachella, Imperial, Palo Verde, Ventura and San Diego



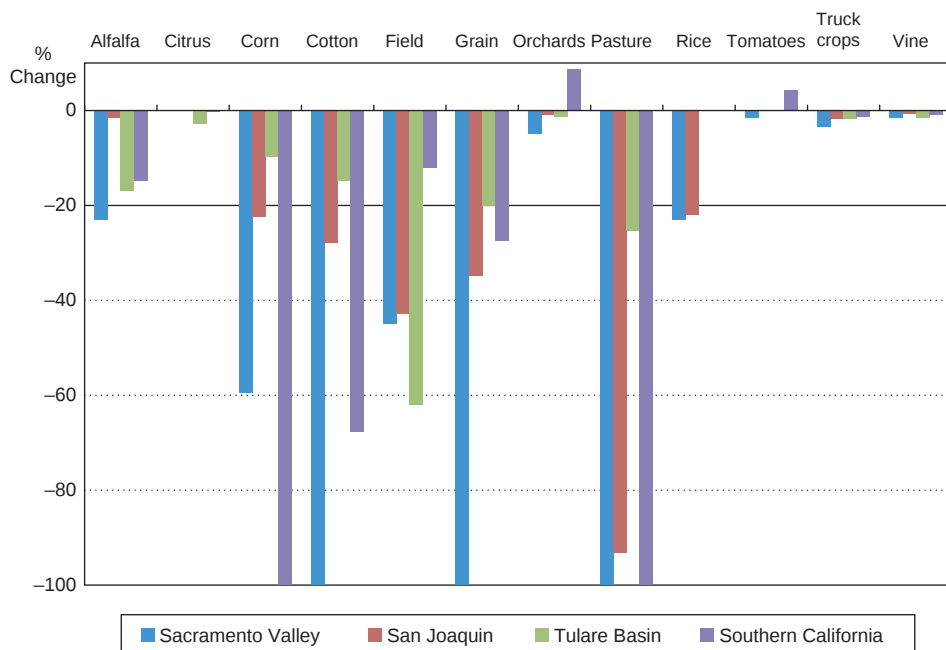
Source: Data from Sanstad et al. (2008).

Figure 15.4 Urban footprint 2005 versus 2050



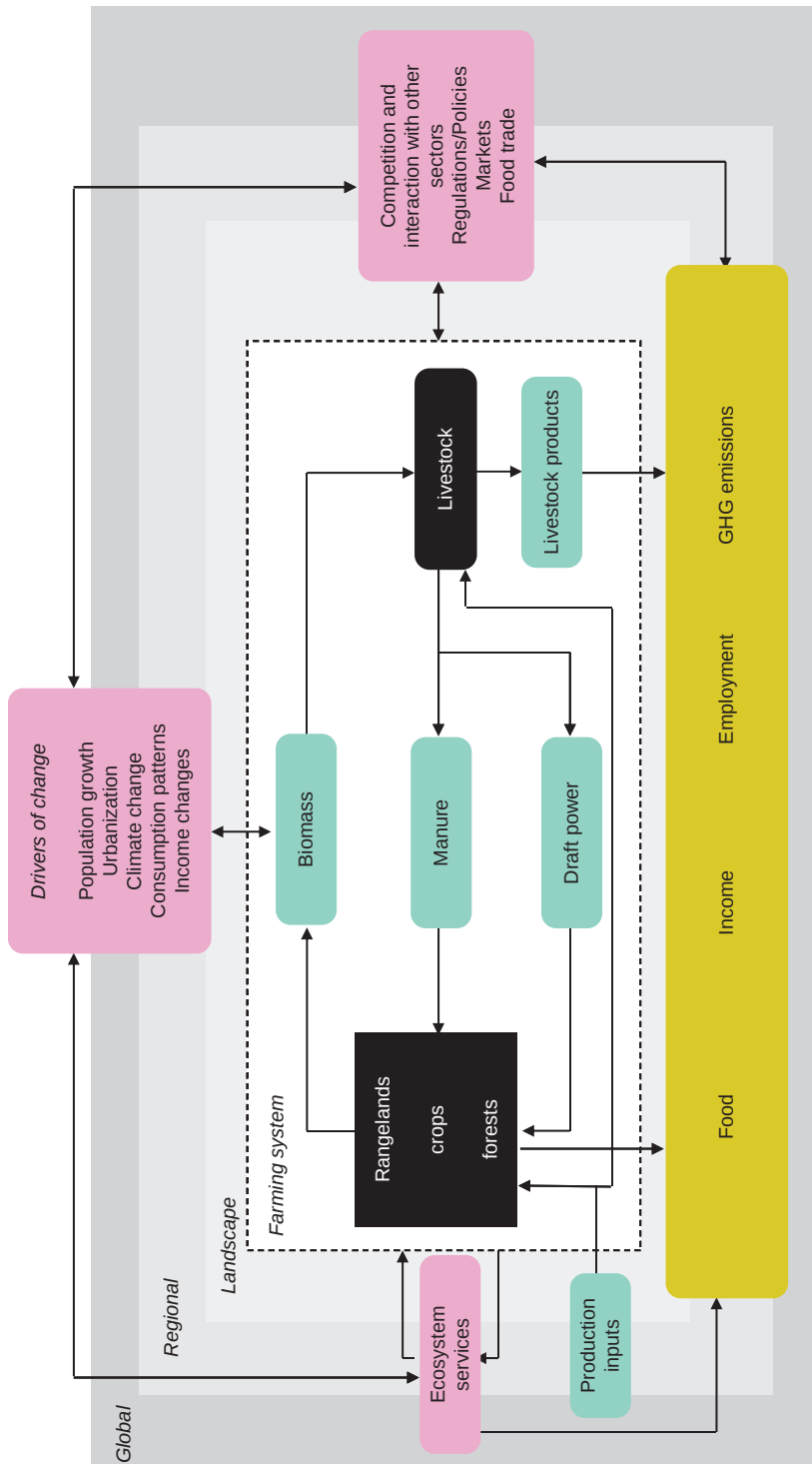
Source: Adapted from Medellín-Azuara et al. (in press).

Figure 15.6 Percentage change in land, water use and agricultural revenues between historical and climate change scenarios by year 2050



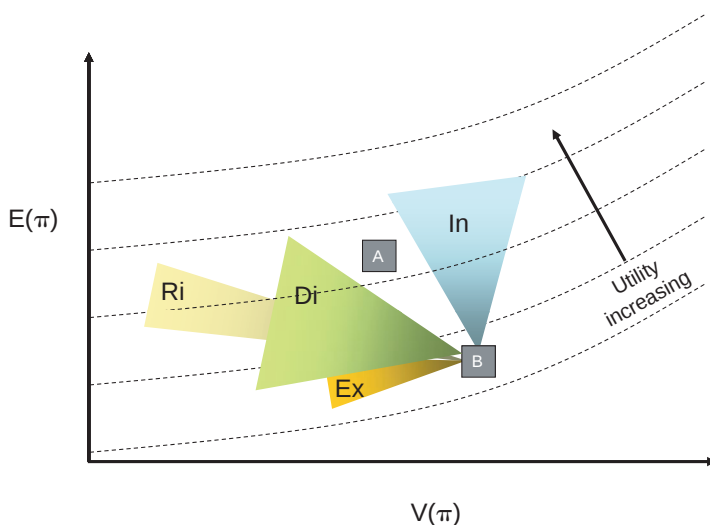
Source: Adapted from Medellín-Azuara et al. (in press).

Figure 15.7 Percentage change in crop area between historical and climate change scenarios in year 2050



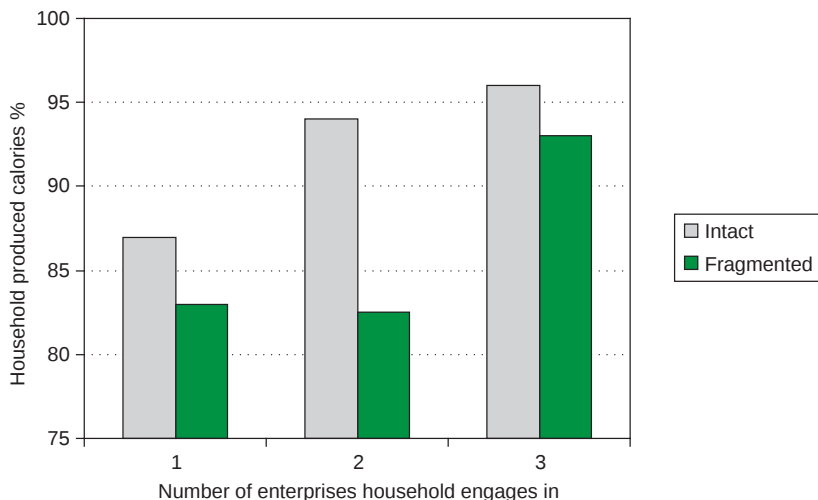
Source: Herrero et al. (2010), with permission from *Science*.

Figure 18.1 The major interactions in mixed crop–livestock systems in the developing world



Notes: $E(\pi)$ mean (expected) income. $V(\pi)$ =variance of income. Colored areas show where the household might move to, for options associated with In=intensification; Di=diversification; Ex=extensification; Ri=risk management. Iso-utility curves shown in grey.

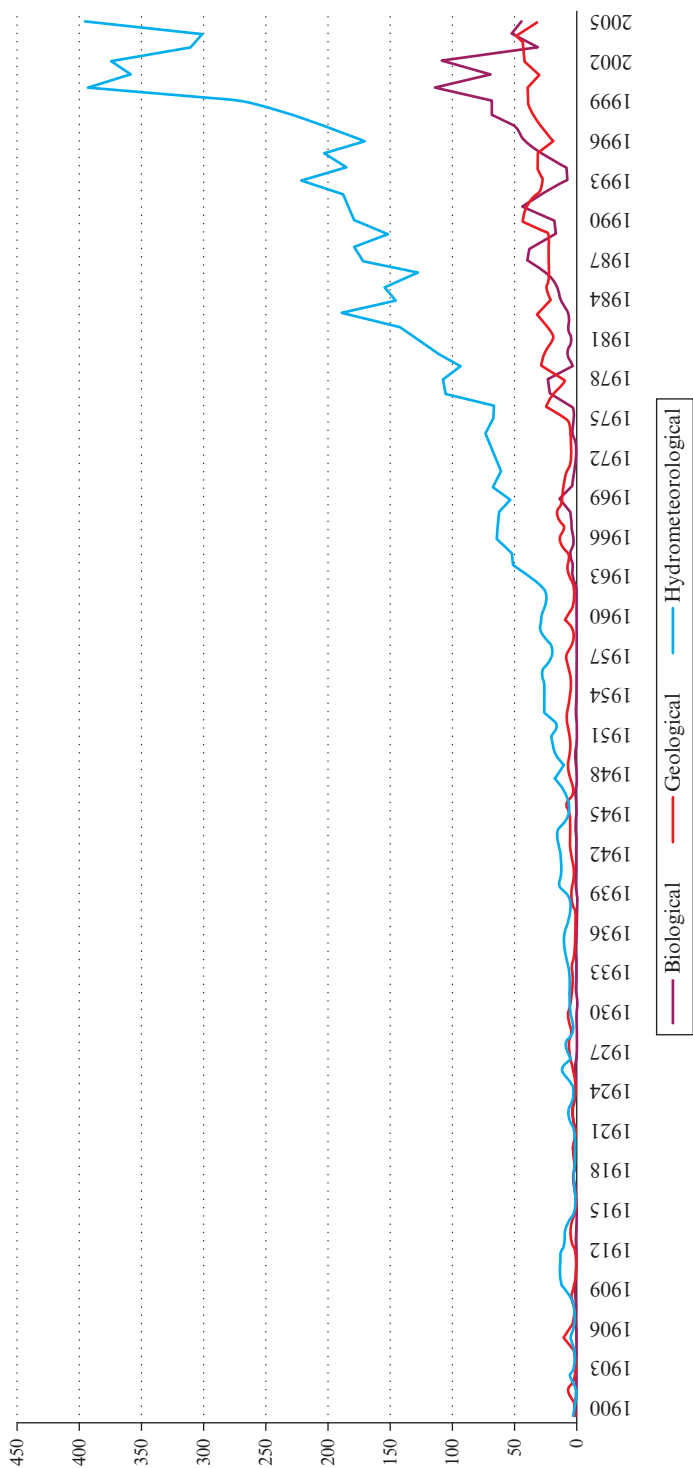
Figure 18.2 Household-level options to address climate change in mean-variance space (highly idealized), following abrupt or gradual change that shifts the household from point A to point B



Notes: (1=livestock only; 2=livestock and a business or irrigated agriculture; 3=livestock, a business, and irrigated agriculture) for two scenarios: the Group Ranch is intact, and the Group Ranch is fragmented to 196-km² parcels.

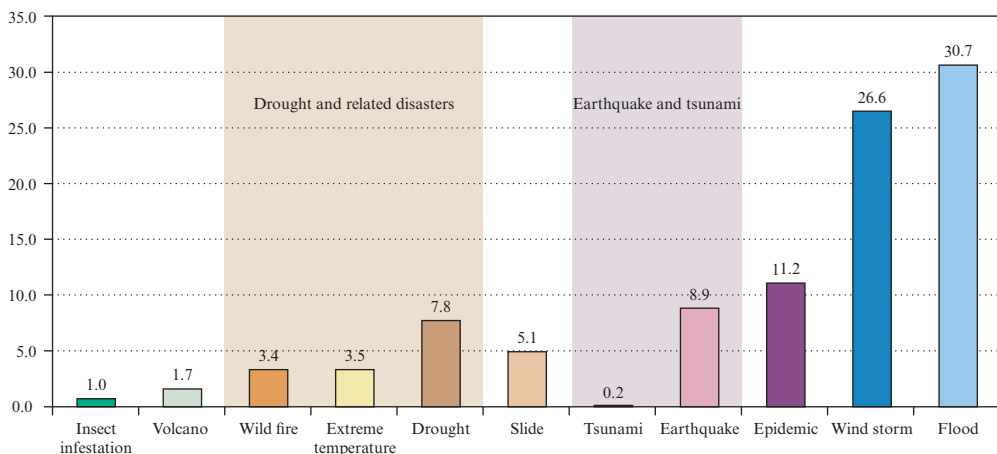
Source: Data from Thornton et al. (2007).

Figure 18.3 Simulated proportion of calories produced within poor households in Imbirikani Group Ranch, Kajiado, that are engaged in different activities



Source: Centre for Research on the Epidemiology of Disasters (CRED); Emergency Events Database EM-DAT <http://www.emdat.be/>.

Figure 19.1 Number of natural disasters registered in Emergency Events Database, 1900–2005



Source: Centre for Research on the Epidemiology of Disasters (CRED); Emergency Events Database EM-DAT <http://www.emdat.be/>.

Figure 19.2 Distribution of natural disasters by type, 1991–2005 (in percentages)

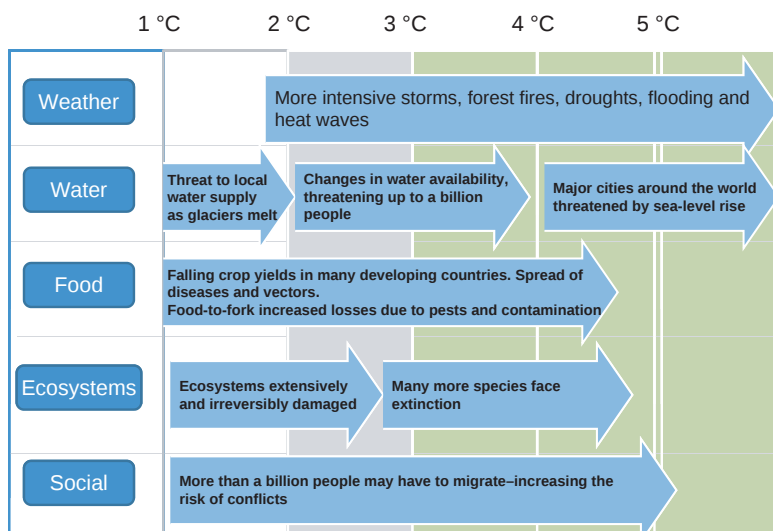
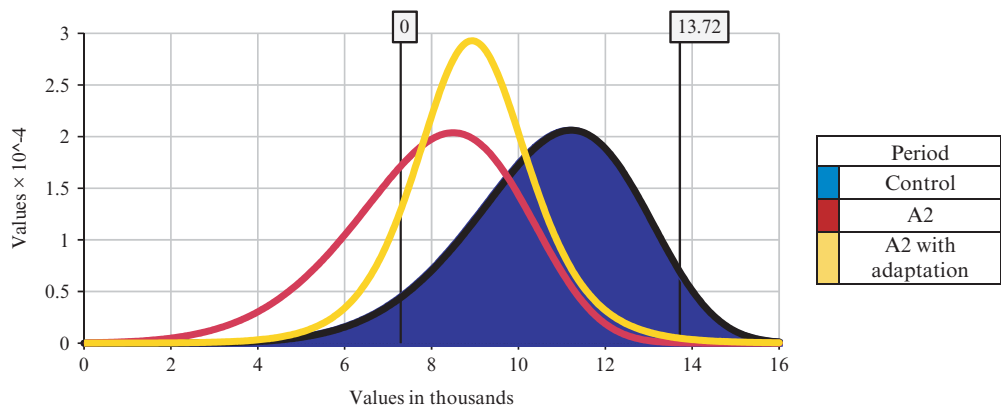


Figure 19.3 Temperature above pre-industrial–IPCC Scenario A1B



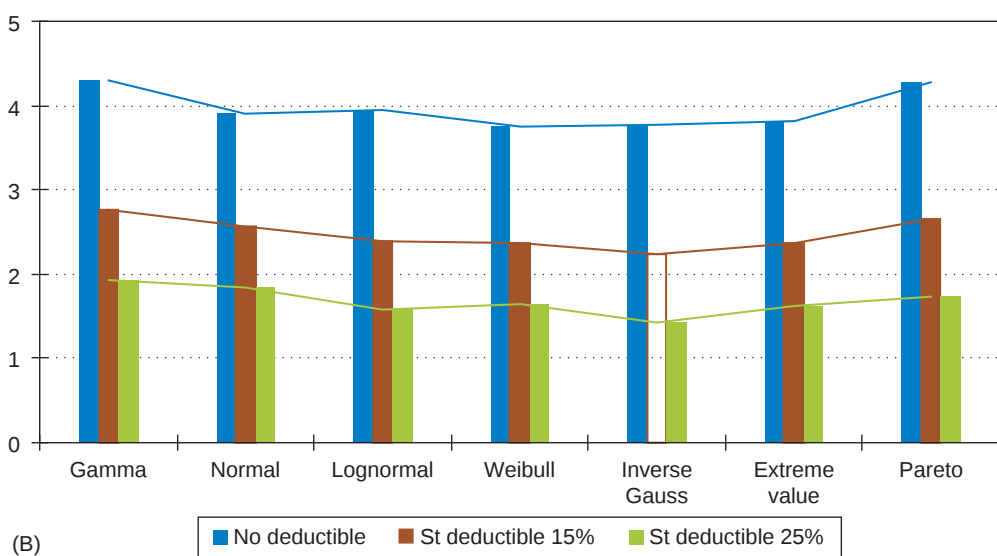
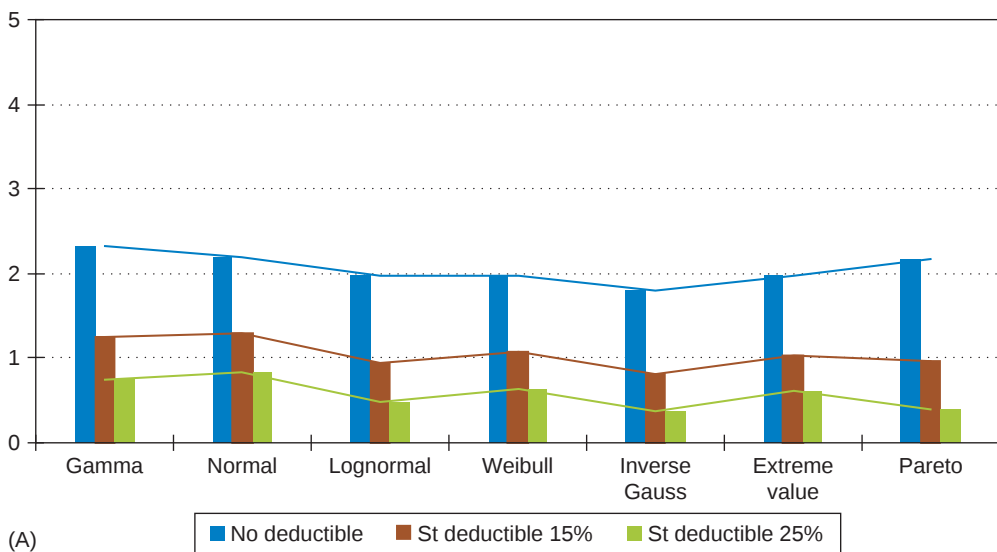
Source: Map from Wikipedia.

Figure 19.4 Study areas in the Iberian Peninsula



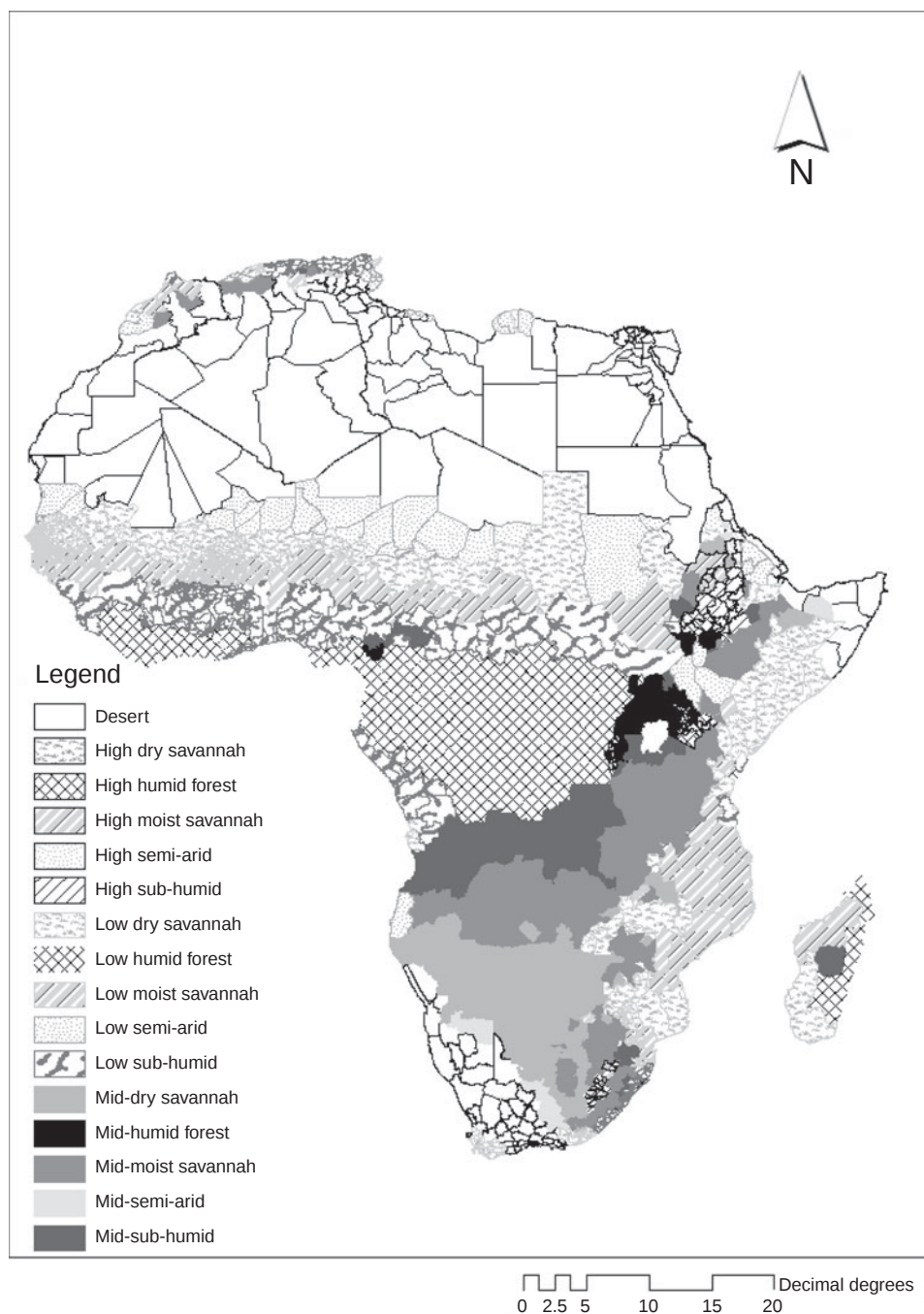
Source: Rey Vicario (2010).

Figure 19.5 Maize yield density functions in the Ebro area



Note: 1 Quintal (Qn)= 100 kg.

Figure 19.8 Premiums (in Qn/ha) for different distribution functions: A: 80% coverage; B: 100% coverage



Source: Seo et al. (2009).

Figure 20.1 Agro-ecological zones of Africa

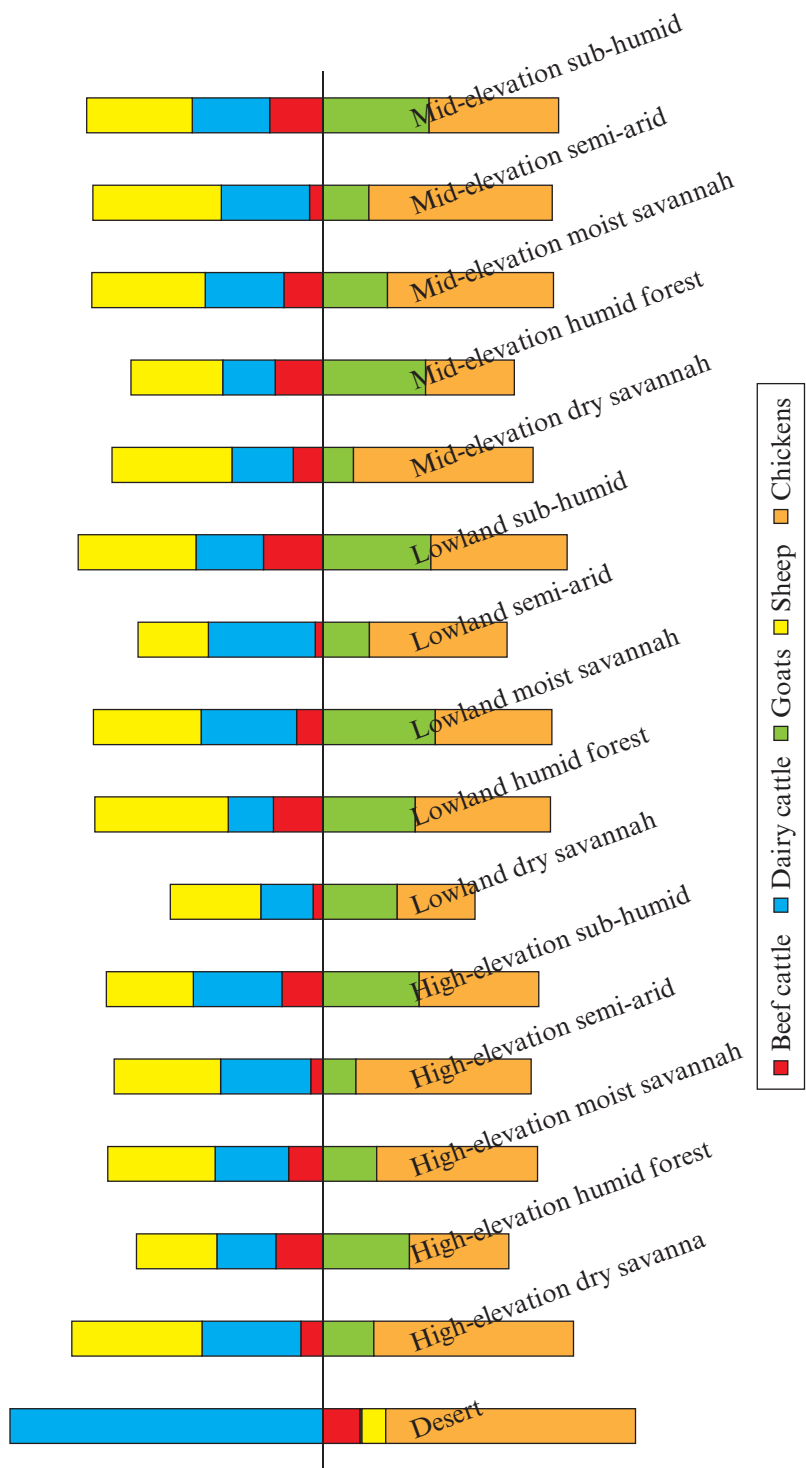


Figure 20.4 Differential impacts across AEZs under the CCC scenario in Africa

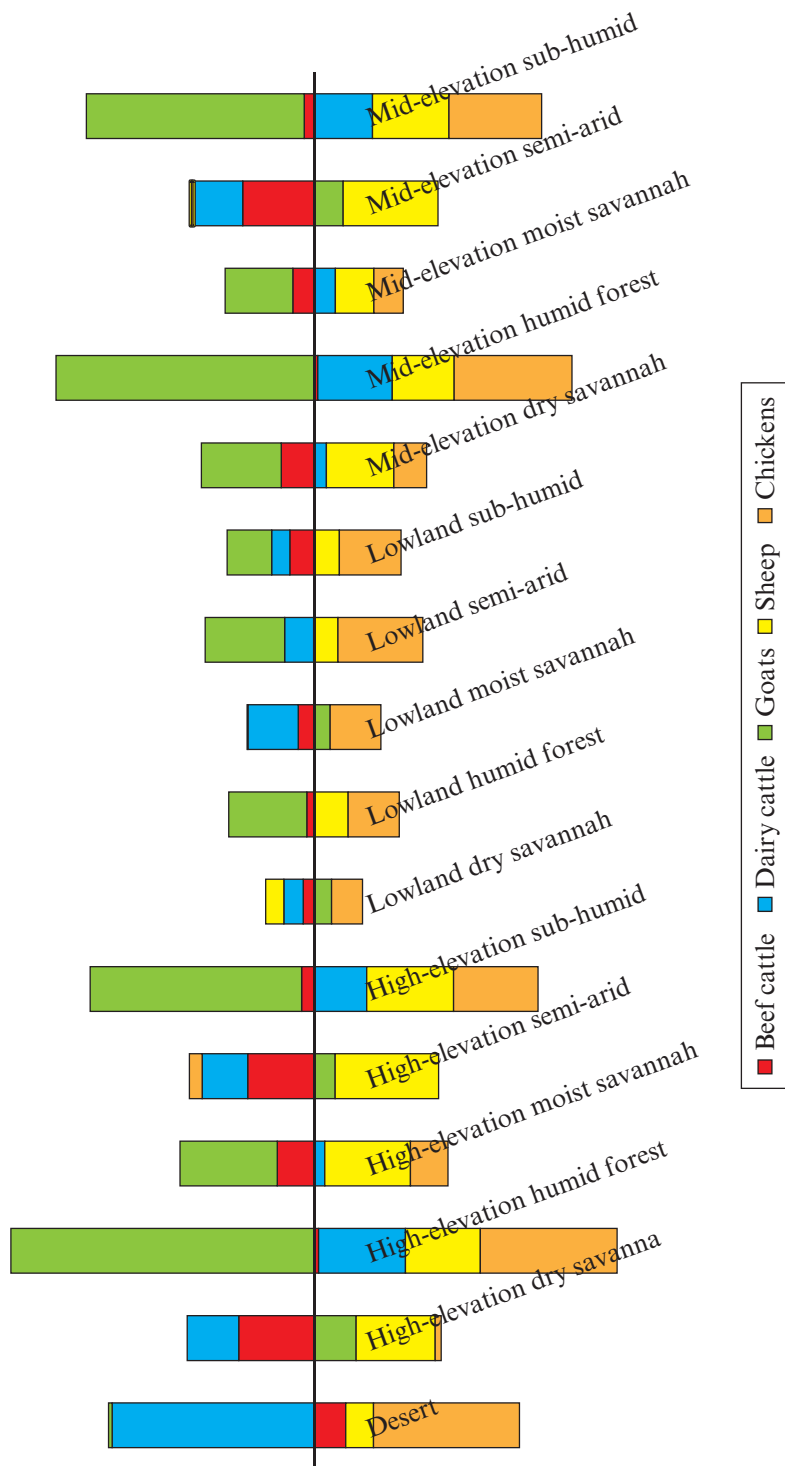


Figure 20.5 Differential impacts across AEZs under the PCM scenario in Africa

PART IV

AGRICULTURAL MITIGATION

12 Biofuels and climate change

Gal Hochman, Deepak Rajagopal and David Zilberman

INTRODUCTION

Greenhouse gas (GHG) emissions from human activities threaten to alter the global climate and can have adverse consequences on the well-being of life on earth. Human activity is probably the primary cause of global warming since 1950 (IPCC, 2007), with fossil fuel use being the primary source of the increased atmospheric concentration of carbon dioxide (CO₂), and land-use changes providing another significant but smaller contribution of about 20 per cent, according to the Intergovernmental Panel on Climate Change (IPCC) (2007). These land-use changes, including intensive farming and deforestation, release large amounts of CO₂ sequestered in the land and in the plant materials to the atmosphere.

Energy derived from plant materials in the form of biofuels can reduce GHG emissions because energy embodied in biofuels is sequestered through photosynthesis and the biofuels can replace fossil fuels. Thus, in theory, biofuels should provide an effective means to mitigate GHG emissions. The reality of biofuel is more complex, however. The production and processing of biofuel requires energy, and that may result in positive net GHG emissions. Biofuels may also accelerate deforestation and land-use changes, resulting in a large amount of CO₂ emitted into the atmosphere. These emissions of GHG associated with the production and utilization of biofuels should be addressed by biofuel policies.

The policy initiatives that provide support for the production of biofuels are not only the ones induced by concerns about climate change but are also the product of concerns for energy security, the depletion of crude-oil reserves and farm income. There are various biofuel policies and they target multiple objectives, sometimes in a piecemeal fashion. While some policies were introduced mostly to address energy security and farm income concerns, others aim to target the environmental objectives.

This chapter aims to address the environmental implications of expanding biofuel production. However, given that biofuel policy initiatives address multiple objectives, the policy discussion is not restricted to the discussion of policies targeting environmental objectives and environmental implications of biofuel policies. Instead, the policy analysis and discussion is expanded to include the complementarities among the various biofuel instruments, which have been either deployed and/or suggested in the literature (de Gorter and Just, 2008, 2009a; Lapan and Moschini, 2009; among others).

The next section provides a brief overview of biofuels. Then, we address some of the environmental impacts and tradeoffs associated with the introduction and expansion of biofuels. In a following section we present a comprehensive survey of existing biofuel policies and their implications. Discussion and concluding remarks are offered in the final section.

BIOFUELS AND THE IMPLICATIONS OF INTRODUCING THEM

The use of renewable energy sources is becoming increasingly necessary to meet the growing demand for energy, especially given the mounting concerns for the environment (i.e. climate change). Oilsands and coal to liquid can substitute for conventional fossil fuel sources, but the implications for climate change can be calamitous. Although fossil fuels have been the predominant sources of energy in the twentieth century, alternative forms of energy are needed in the twenty-first century to meet growing needs, especially given the projected growth in world population and the purchasing power of consumers in countries such as China. The world population grew from 2.5 billion in 1950 to 6.5 billion in 2005, and is projected to climb to 9 billion by the end of the current century. Whereas the global average of primary energy in 1990 was 1.67 tonnes of oil equivalent per capita, it reached 1.78 in 2005. Moreover, energy consumption is an S-shaped function of income and it is taking off at the income levels associated with high adoption rates of cars. For instance, the gross domestic product (GDP) per capita for China in constant 2000 US dollars was 105 in 1960 but reached 1451 in 2005, and it has been growing further since. Car ownership in China is spreading and demand for fuel is growing rapidly. This growing demand is raising the gains from introducing new sources of fuel supplies.

Biomass: A Promising Renewable Energy Source

Biomass is in essence a form of solar energy embodied in organic materials, including trees, crops and organic waste, which has been utilized by humans for millennia. In 2004, about 80 per cent of the global supply of renewable energy comprised renewable combustibles such as wood, dung, charcoal and agricultural wastes. This form of energy was consumed mostly in non-Organisation for Economic Co-operation and Development (OECD) countries. Developing countries in Africa and Asia combined for 67 per cent of the global use of renewable energy. From an end-use energy perspective, 58 per cent of the renewable energy is consumed by the residential, commercial and public sector mostly for cooking and heating (Rajagopal and Zilberman, 2007).

Biomass and electricity

Biomass can be used to produce electricity, and is much more efficient at this than in providing transport energy. Biomass is twice as effective in reducing GHG emissions when used to displace fossil electricity than when used to displace oil (Campbell et al., 2009). Qin et al. (2006) calculate that cofiring 10 per cent switchgrass (a perennial grass) and 90 per cent coal resulted in a 6.3 per cent reduction in the overall life cycle of CO₂ emissions relative to that from burning pure coal. They also find that GHG emissions per tonne of switchgrass are lower under cofiring than under switchgrass fired alone because of the higher thermal efficiency of switchgrass under cofiring. When compared to other renewable energy sources used to generate electricity, biomass to electricity is predicted to have high growth rates (although the total amount of electricity generated by biomass is relatively small compared to other renewables such as hydro). To this end, the Energy Information Administration (EIA) (2009) predictions are that, from 2007 to 2030, the

annual growth rate of electricity generation from biomass will be 6.4 per cent – a growth rate that is second only to solar (photovoltaic and thermal), which is 6.9 per cent.

When compared to other renewable sources, biomass is used extensively to produce heat and generate electricity, but is used much less as transportation fuel. Although in OECD countries 15.4 per cent of electricity in 2007 was generated from renewable sources, only 1.7 per cent came from renewable combustibles and waste. However, due to its widespread use in developing countries, solid biomass (organic, non-fossil material of biological origin, which may be used as fuel for heat production or electricity generation) is by far the largest renewable source, representing 9.3 per cent of total primary energy supply or 73 per cent of global renewable supplies. However, the share of liquid biomass (fuels and bioadditives, such as ethanol and biodiesel) in the global renewable energy supply was only 2.4 per cent. In 2007, world total primary energy supply was 12 026 million tonnes of oil equivalent, of which 12.4 per cent was produced from renewable energy sources. The share of other energy sources included 34 per cent oil, 26.4 per cent coal, 20.9 per cent natural gas and 5.9 per cent nuclear energy (IEA, 2009).

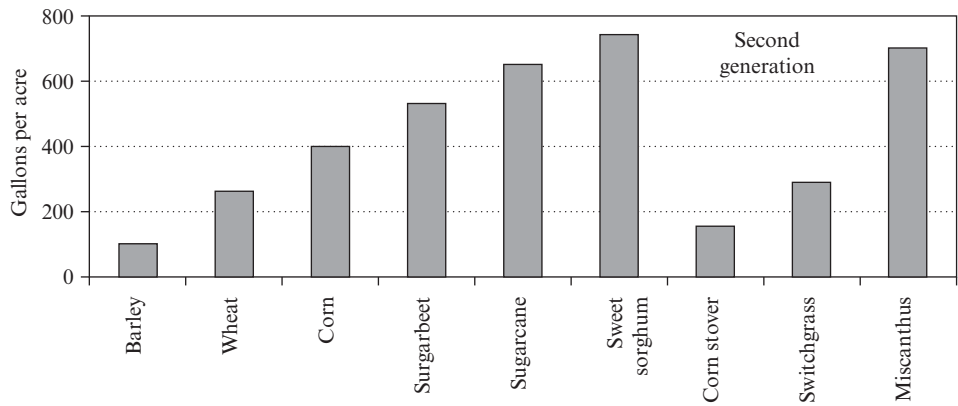
The use of biofuel in the transportation sector

A major use of biofuels is as liquid fuels for transportation. Transport fuels can be classified as fossil fuels and renewable fuels, and the renewable fuels are further classified based on the different primary energy sources needed to produce fuels, and the technology used to liquefy the biomass. For example, biodiesel can be produced directly from oil-containing plants whereas ethanol can be processed from sugar, starch and cellulose. In addition, biomass can be liquefied to yield 'biocrude' or be gasified. Biofuels can be further categorized into first- and second-generation biofuels. Whereas the technology used to produce the first is matured, the technology used to produce the latter is at the R&D stage (Rajagopal et al., 2009).

First-generation biofuels are based on sugar, starch and oilseed crops. The bioethanol feedstock is produced from any biological feedstock that contains appreciable amounts of sugar or materials that can be converted into sugar, such as starch. Two examples of feedstock for ethanol production are sugar beets and sugarcane, which contain high percentages of sugar. Sugars can be easily fermented. Corn, wheat, barley, rye and other cereals are typical feedstock, containing starch in their kernels. Starch can be easily converted into sugar and then into ethanol. The technology used throughout the first-generation biofuels production chain has matured and involves four stages, namely, cultivation and production of raw material, processing into fuel or electricity, distribution and retail and end use.

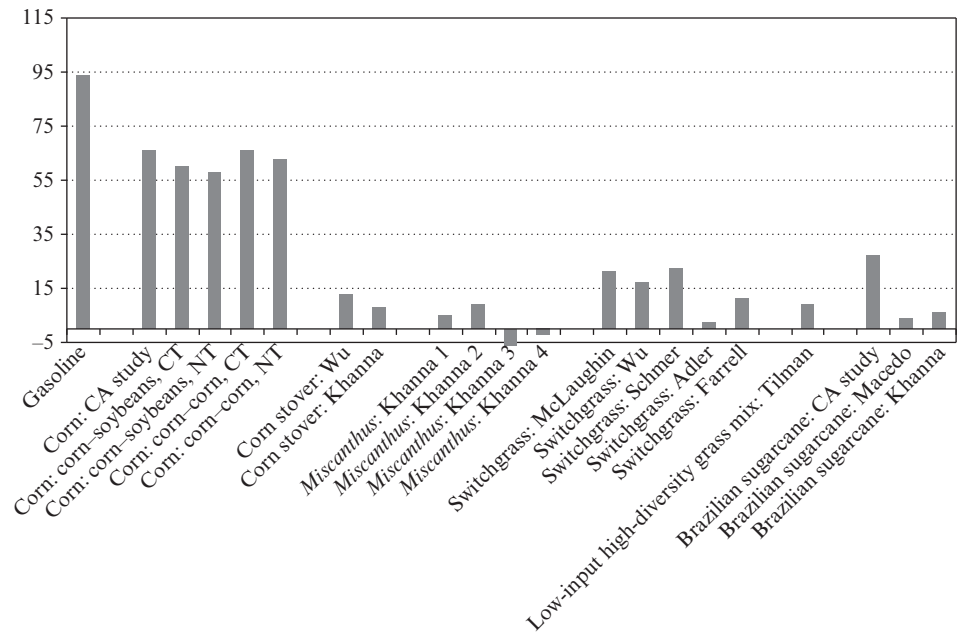
The Brazilian sugarcane is emerging as an efficient and relatively 'clean' first-generation biofuel (Figures 12.1 and 12.2). The ethanol yield per acre of Brazilian sugarcane is equivalent to the amount produced by some of the better second-generation feedstocks (Figure 12.1), and the amount of gram CO₂ (gCO₂) it emits is on the low side when compared to both first- and potential second-generation feedstocks (Figure 12.2). These numbers are expected to improve significantly in the future as Brazilian sugarcane production will use more bagasse for electricity production. It currently uses about 20 per cent of the bagasse, but this is expected to increase substantially in the near future.

Lipid sources can be used to produce biodiesel. Some examples of lipid feedstock sources include palm fruits, algae, seeds and waste oil. Although the productivity of palm fruits is the highest, the most common feedstock sources for pure plant oil and



Source: Khanna (2009).

Figure 12.1 *Yields of various biofuel feedstock*



Source: Khanna (2009) and references therein.

Figure 12.2 *GHG emissions from various biofuel feedstocks*

biodiesel production are seeds from various plants. These include seeds from ricinus, sunflower, peanut, sorghum, rapeseed and *Jatropha*. The choice for a dedicated feedstock is predetermined by agricultural, geographical and climatic conditions. However, it must be taken into account that different feedstock types are characterized by different properties.

Unlike the first generation, the second-generation feedstocks provide opportunities to use nearly the whole plant for biofuel production, and not only parts of the plants (grains, tubes, stalks). In order to use second-generation biofuels for ethanol production, advanced technologies are necessary (Rajagopal et al., 2009). A large variety of feedstock is available for producing ethanol from biomass that contains large amounts of cellulose and hemicellulose, which can be converted to sugar though with more difficulty than starch. There are significant ongoing R&D efforts to improve the conversion of the various sources of cellulosic biomass that include energy crops, agricultural wastes (including those resulting from conventional ethanol production), forest residues, municipal solid waste and wastes from pulp/paper processes. The dedicated energy crops grown specifically for ethanol production include fast-growing trees (poplars), shrubs (willows) and grasses (switchgrass and *Miscanthus*). The cellulosic content of these materials ranges between 30 per cent and 70 per cent of their mass.

The large-scale production of agricultural ethanol requires substantial amounts of arable land and water (except for wastes). Second-generation biofuels comprise new feedstock (organic waste matter, cellulosic energy crops and algae) as well as new conversion technologies that use microbiological processes to convert feedstock directly into synthetic gasoline/diesel or into butanol, all of which are in the R&D stage. Although production of corn ethanol in the USA is estimated at US\$ 1.49 per gallon (US EPA, 2008), cellulosic ethanol from wood or switchgrass through dilute acid pretreatment and enzymatic hydrolysis was calculated at US\$ 3.97 for 2006, which includes an annualized 20 per cent capitol charge (Solomon et al., 2007). Differences in cost and yield also exist among second-generation feedstock (Jain et al., 2010) as illustrated in Figures 12.1 and 12.2.¹ However, one should be careful in comparing costs across studies because of differences in input costs and in the boundaries of model analyzed.

Second-generation biofuels are expected to be more easily compatible than first-generation ethanol or biodiesel with existing infrastructure for distribution and end use of fuels once the technology breakthrough that will result in a significant price reduction arrives. However, second-generation biofuels may have their own negative unintended consequences. For example, crop residues are important for soils in terms of the hydrological cycle, energy balance, nutrient cycling, food for soil biota, erosion control, water quality, hypoxia, ecoefficiency and agronomic production. Clearly, the importance of these factors depends on the agroclimatic situation but it does suggest limitations that may constrain the use of crop residuals for biofuels.

Schmer et al. (2008) evaluated perennial herbaceous plants, including switchgrass, as cellulosic bioenergy crops. Those authors addressed two major concerns: net energy efficiency and economic feasibility of switchgrass and similar crops. Prior energy analyses were based on data on smaller research plots (less than 5 m²), but Schmer et al. (2008) managed switchgrass as a biomass-energy crop in field trials of 3–9 ha (1 ha = 10 000 m²) on marginal cropland on ten farms across a wide precipitation and temperature gradient in the USA. The costs of inputs, biomass yield, estimated ethanol output, GHG emissions and net energy outcome were derived and reported. Annual biomass yields of established fields averaged 5.2–11.1 tonnes/ha with a resulting average estimated net energy yield of 60 GJ/ha per year. Average GHG emissions from cellulosic ethanol derived from switchgrass were 94 per cent lower than the estimated emissions from gasoline. That study is a baseline that represents the genetic material and agronomic

technology available for switchgrass production in 2000 and 2001 when the fields were planted. Improved genetics and agronomics may improve energy sustainability and biofuel yield of switchgrass further.

An alternative to cellulosic based second-generation biofuels are drop-in biofuels, that is, fuels such as synthetic gasoline that can be put into fuel tanks and pipelines with no modifications. Instead of ethanol, this technology makes hydrocarbons, molecules that are chemically much more similar to those used to power planes, trains and cars. This technology produces the molecules using genetically engineered bugs, which not only guarantees consistent quality but also enables companies to use cheap and efficient feedstock, such as Brazilian sugarcane. Tariffs that block Brazilian ethanol from the Northern hemisphere do not apply to drop-in hydrocarbons. But, once these technologies become commercial, the politics may change this advantage. There are other alternatives, such as butanol, which are much closer to the gasoline than ethanol. However, all of these technologies are at the R&D stage and are not yet commercially viable.

The Unintended Environmental Consequences from the Introduction and Expansion of Biofuels

Biomass emerged at the beginning of the twenty-first century as a promising solution to mitigating GHGs. But reality proved more complex, and the technological advancements required for second-generation biofuels to become commercial are much more challenging than initially thought. Although the introduction of biofuels is likely to have lowered fuel price because some biofuels displace fossil fuels (Hochman et al., 2011; Drabik and de Gorter, 2010), the introduction of biofuels may have resulted in an increase in GHGs attributed to the increase in total fuel consumption. Recall that current-generation biofuels require energy for production (Hochman et al., forthcoming; Drabik and de Gorter, 2010) and lead to land-use changes (Hertel et al., 2010; Tyner et al. 2010), which probably result in biofuels with positive GHG emissions.

GHG emissions from biofuel feedstock production have two primary sources: fossil fuels and land. Biofuels produced from ligno-cellulosic feedstocks would have distinct advantages over current biofuels in both respects. Crop and forest residues, animal manure and municipal waste – all parts of existing product streams – can be collected with minimal use of fossil fuels and with little or no effect on GHG sequestered in the soil. Compared with corn, dedicated fuel crops can be grown with the use of less diesel for running farm equipment and less natural gas for producing nitrogenous fertilizers (Farrell et al., 2006). A number of recent studies have consistently shown that biofuels produced from ligno-cellulosic biomass are likely to emit less GHG than petroleum-based fuels (Tilman et al., 2001; Farrell et al., 2006) if there are no indirect GHG emissions from the conversion of native ecosystems to plant displaced crops (Fargione et al., 2008; Searchinger et al., 2008), and assuming that biofuels replace, not displace, fossil fuels.

The rising price of corn, in part due to the introduction of first-generation biofuels, led to an increase in intensification and application of fertilizers, expanding nitrogen runoff into the ‘dead zone’ in the Gulf of Mexico. Enforcing stricter water quality and adopting precision farming could have reduced these negative side effects. One of the main advantages of perennial second-generation crops, such as *Miscanthus*, is that they use nitrogen more economically (Khanna, 2009). Lower nitrogen-fertilizer requirements for

dedicated fuel crops also lead to lower nitrous-oxide emission directly from the soil and indirectly from nitrogen runoff into waterways. Furthermore, perennial biomass crops may increase soil-carbon sequestration compared to corn even with conservation tillage practices (Baker et al., 2007).

THE BASIC TRADEOFFS AND THEIR RESOLUTION

Globalization has led to capital intensification as well as the increase in demand for consumer goods and food in developing countries. For example, globalization has contributed to China becoming the ‘workshop of the world’ and the biggest importer of food products, such as soybeans and energy. Globalization led to the increase in the price of energy, which contributed to the emergence of biofuels. The introduction of biofuels and the increase in demand for food contributed to the increase in food prices (Hochman et al., 2010). The increased demand for food and fuel also contributed to a significant increase in GHG emissions. Therefore the challenge is to design policies that can lead to sustainable growth while controlling GHG emissions and meeting the growing demand for a higher standard of living. To design sustainable-growth solutions and identify the role of biofuels in these solutions, we need to understand the processes and linkages that contributed to the current state of affairs.

In the following sections, we elaborate on the various tradeoffs resulting from the introduction and expansion of agriculture-based energy sources.

GHG Emissions and the Introduction and Expansion of Biofuels

The major challenge is to slow or even reverse the accumulation of GHGs to a level that is tolerable. This would require policies that would induce reduction in GHG emissions and lead to carbon sequestration and storage. Such policies are especially challenging given population and economic growth in developing economies and political difficulty to induce changes globally.

The reduction in GHG emissions may require modification in behavior as well as drastic changes in technology. Given that the main contributors to GHG emissions include energy sources from fossil fuels (such as oil and coal), deforestation in tropical forests and land-use management practices (IPCC, 2007), reduction in GHG emissions can be achieved by reducing energy consumption, increasing energy-use efficiency, using cleaner energy sources, adopting improved agricultural and forestry practices and introducing carbon sequestration and storage technologies. Existing technologies can meet some of these challenges, but the set of technological tools needs to be augmented by successful outcomes of new R&D efforts. These successful outcomes that result in technological change may be associated with large changes in investment and in the capital composition as well as changes in behavior.

Land-use Changes and the Introduction and Expansion of Biofuels

Fossil fuels are nonrenewable resources that are consumed much faster than nature can create them. It takes nature millions of years to create fossil fuels but humanity just one

year to consume 474 exajoules (474×10^{18} J). For example, in 2008, 80 to 90 per cent of energy came from fossil fuels, that is, 87 million barrels of crude oil a day. Fossil fuels cannot be replaced as fast as they are being consumed. Eventually, fossil fuels will become too costly to harvest and humanity will need to find other sources of energy. While oil consumption in the world is increasing, oil extraction and production in non-OPEC countries is decreasing. The EIA predicts that, although non-OPEC liquid supply grew by 630 000 barrels per day (bbl/d) in 2009, in 2010 the growth rate will probably be 420 000 bbl/d and that it is likely to decline by 140 000 bbl/d in 2011. In contrast, EIA expects the demand for world fuel liquids to grow by 2.55 million bbl/d between 2009 and 2011.² At present, the main energy sources used by humans are non-renewable as they are cheap to produce, but this energy paradigm is likely to change in the future.

Thus it is important to incorporate dynamic aspects of fossil fuels so as to understand the implications of consuming a non-renewable resource and of replacing these non-renewable resources with renewable resources, such as biomass. To this end, Chakravorty et al. (2008) model the tradeoff between producing clean energy produced with land and using land for food production, and show that clean energy may substitute for a polluting non-renewable resource, such as oil. In particular they argue that when fossil fuel (produced from a polluting nonrenewable resource) is abundant and the price of food is sufficiently high, only fossil fuels will be consumed. As the non-renewable resources are depleted, there will be a certain point in time where some land will be allocated to fuel production and a transition period will exist where both the renewable fuels (the clean energy produced with land) and the fossil fuels will be utilized. At a certain point in the future after the transition period, the use of the non-renewable resources to produce fuel will stop and consumers will utilize only renewable fuels (see also Chakravorty et al., 2009). The expansion of energy sources to renewable energy and the introduction of biofuels increase the demand for land, which is expected to grow in the future unless changes in technology and behavior mitigates the rise in demand for energy and increases agricultural productivity.

Some of the renewable fuels replace fossil fuels, and the rest expand the fuel supply. Overall consumption of fuels is expanded with the introduction of biofuels. Thus, if the new sources are not sufficiently clean, it may lead to an increase in GHGs (Hochman et al., 2011; Drabik and de Gorter, 2010). Thus both the replacement and the displacement effect of biofuel have to be taken into account when designing biofuel policies that aim to reduce GHG emissions.

Food versus Fuel

The introduction of biofuels had unintended consequences on world food prices (Hochman et al., 2011). Even though biofuels were not the main contributor to the food-price inflation of 2007–08 and the crisis, to a large extent, was a product of years of growing demand for food resulting from industrialization and economic growth in Asia and elsewhere unmatched by an increase in agricultural productivity (Trostle, 2008), the diversion of some food commodities to biofuels made the situation more acute. The food-price crisis might have become more acute with agricultural biotechnology, which contributed to a significant increase in the supply of corn and soybeans (Sexton and Zilberman, 2010). Investment in agricultural biotechnology has slowed, however,

in part because of regulation and bans in Europe and elsewhere. These results suggest that efforts to increase agricultural productivity, including expanding the utilization of agricultural biotechnology and investing in second-generation biofuels, may be needed as part of the sustainable-growth solution to the current GHG situation.

The International Oil Market and its Implications for Biofuel Regulation

The introduction of biofuels affects fuel prices as well as quantities and composition of fuels consumed. The magnitude of its impact is influenced by market structure. Hochman et al. (2011) argued that the current oil-pricing system, which has a large gap between the international price of oil and the price in OPEC, is consistent with the a cartel-of-nations model whereby the oil-exporting countries use their monopoly power to extract revenue from the oil-importing nations while pursuing cheap oil policies domestically. Within this framework, the introduction of first-generation biofuels is likely to reduce fuel prices and fossil-fuel production but increase overall fuel consumption. Furthermore, biofuels may reduce GHG emissions if they are relatively clean, but first-generation biofuels increase total GHG emission. This research identified large differences between the effects of introducing biofuels using the cartel-of-nations model in contrast to the competitive or the standard cartel model. These differences are expected to grow as domestic fuel consumption in OPEC increases.

BIOFUEL POLICIES: OPTIMALITY MEETS REALITY

Economic theory distinguishes two types of externalities: technical externality and pecuniary externality. Technical externalities are unintended physical outcomes produced by economic agents that directly affect other economic agents. The technical externalities include burning fuels to produce biofuels, which emits GHGs that contribute to global warming – a ‘public bad’. It also includes taking land away from nature and using it to produce biofuels, which, on the one hand, contributes to global warming (global public bad) but, on the other hand, affects biodiversity and open spaces (local public good). The other type of externality, the pecuniary externalities, is the outcome of action by economic agents that affects market prices and thus alters other agents’ behavior. These include the indirect land and fuel effects identified in the literature.

Hochman et al. (2010) depict the social optimum solution of a model that internalizes all of the externalities associated with biofuels and offer a vantage point that can be used to access the implications from existing climate change and biofuel policies. They show that, at the social optimum, policy should not address indirect effects (i.e. pecuniary externalities) but only technical externalities. However, the reality is that policy makers are contemplating whether to price the indirect land effects (i.e. the pecuniary externalities).

We therefore describe the optimal policy and shed further light on existing policy and the objectives that guide policy makers. While Hochman et al. (2010) offer a welfare-economic perspective to assess climate change and biofuel policies, it cannot explain the existing regulations. Policy making is done in a piecemeal manner, and each legislation emphasizes certain policy objectives and is hindered by financial, ecological and political

constraints (Zilberman et al., 2010). For example, existing regulations of biofuel policies in the USA are part of the energy security legislation that aims to reduce dependence on and import of foreign fuel (Energy Independence and Security Act of 2007). But this Act addresses concerns for GHG emissions from biofuels by establishing the Renewable Fuel Standard (see US EPA, 2008), which sets an upper bound on life-cycle GHG emissions per gallon of biofuel.

GHG Emissions and Biofuels

The efficient response to the negative externalities associated with energy production and use is to impose a Pigouvian tax on polluters that equals the marginal cost of pollution (Pigou, 1938). Thus the first-best response to GHG emissions is the imposition of a global carbon tax on each unit of emissions equal to the marginal externality cost of carbon emissions (e.g. Mankiw, 2007; Metcalf, 2007; Glaeser, 2008; Nordhaus, 2008; Shapiro et al., 2008). Such a tax would improve social welfare by reducing carbon emissions while creating no deadweight loss. It would internalize the technical externality associated with GHG emissions (Hochman et al., 2010). It would also generate government revenue that could be used to reduce other taxes that do cause distortions, such as income taxes, thus providing a double dividend (Goulder, 1994; de Gorter and Just, 2009b).

A carbon tax is a policy that provides appropriate incentives throughout the energy market without choosing technology winners and losers (Fischer and Newell, 2004). It encourages traditional energy producers to reduce the emissions intensity of fuels, renewable energy producers to increase output and invest in R&D to lower costs and consumers to conserve energy. If biofuels are emitting less GHG than fossil fuel, a carbon tax will provide an extra incentive to their introduction. Furthermore, a carbon tax will provide an extra edge to clean second-generation biofuels or sugarcane ethanol compared to corn ethanol.

A system of tradable carbon emission permits can be equivalent to a carbon tax in terms of efficiency if the aggregate quota is set to equate demand with private marginal cost plus marginal externality cost, and if the government auctions the permits. Europe instituted a system of tradable permits in 2005 with a quota of permits that gradually declines to impose greater and greater pressure for carbon emissions mitigation. However, by 2007, the carbon quota was still higher than total emissions and the price of a carbon emission permit had plummeted to near zero. Similar attempts in the USA continue to be unsuccessful politically.

When setting carbon policy, discounting uncertainty and political economy considerations should also be addressed, thus making this discussion much more complex (de Gorter and Tsur, 2010). For example, politicians may prefer cap and trade because the distribution of rights is a source of political power. The Kyoto Protocol was one attempt to develop a global framework to address climate change. However, it did not yield a carbon tax but a cap-and-trade system that is not global. Many countries have introduced biofuel policies. Usually these policies set a lower bound for the fraction of fuel supplied by biofuels. Reduction of GHG emissions seems to be secondary in these biofuel policies. The narrative accompanying many of these policies emphasized energy security as a major objective. Furthermore, all biofuels with GHG emissions below a certain threshold level are treated alike. The only type of biofuel policy that has GHG

emphasis is the Low Carbon Fuel Standard (LCFS), where an upper bound is set on the pollution intensity of the end fuel consumed. Some of the subsidies to biofuel can be interpreted as a part of long-run GHG policy but, as Cui et al. (2010) have shown, the US biofuel policy embodied in the Energy Independence and Fuel Security Act of 2007 does not contribute much to reducing GHG emissions.

Related to fuel taxes are fuel standards that require fuel producers to meet carbon-intensity standards. California is pursuing the LCFS in its effort, codified by legislation, to reduce GHG emissions to 1990 levels by 2020. The California standard, modeled after a similar policy in the UK, requires producers of transportation energy to track and report the 'global warming intensity' (GWI) of their fuels (measured as the production of global warming materials per unit of energy) and to reduce the GWI over time (Farrell and Sperling, 2007). The determination of GWI is based on life-cycle analysis. To achieve the GWI reductions with least cost, the LCFS permits end-fuel producers to reduce the GWI by producing cleaner fuels (such as renewable fuels) by purchasing credits from traditional energy firms that exceed their required GWI reductions, or from renewable energy producers. Despite the introduction of a market for GWI reduction credits, the LCFS is inferior to a fuel tax in that it provides no incentive for emission reductions beyond those prescribed by policy (e.g. conservation). In violation of the principle of targeting (which states that distortions, or market failures, should be 'targeted' as directly as possible), the LCFS essentially taxes carbon intensity when carbon emissions have been linked to climate change (Holland et al., 2007). The LCFS, therefore, is associated with greater excess burden than a carbon tax or even a fuel tax. Moreover, biofuels produced on land converted to production from natural habitat (which emits carbon into the air) should not be taxed the same as biofuels produced on existing farmland (Searchinger et al., 2008). Thus payments for carbon sequestration do not result in optimal levels of biodiversity preservation because the monetary value of biodiversity, which varies across regions, is usually not included in the calculations.

The Renewable Transport Fuel Obligation in the UK required oil companies to blend 2.5 per cent biofuel in motor fuel in 2008 and blend 5 per cent by 2010–11. The European Union Biofuels Directive (2003) requires member states to set national targets to ensure a minimum proportion of biofuels and other renewable fuel use in their domestic market. A reference target value for the end of 2005 was set at 2 per cent, calculated on the basis of energy content of all gasoline and diesel for transportation purposes, and 5.75 per cent by the end of 2010 (Kojima et al., 2007). In India, China and Thailand, mandatory blend ratios range from 5 per cent to 10 per cent, while they vary from 20 per cent to 25 per cent in Brazil depending on the supply of ethanol. In January 2007, the State of California formally signaled its intent to enact the world's first GHG standard for transportation fuels (AB32).

The potential for developing win–win synergies between climate change mitigation and adaptation has become a recent focus of both climate research and policy. Carbon offsets are one mechanism currently used to mitigate GHG emissions in agriculture and land use with bioenergy potentially being an important part of the projects. But carbon offsets are not a sufficient mechanism because of transactions costs (related to implementation, monitoring and verification of GHG emission reductions) and carbon leakage. So other forms of financing GHG emission reductions are recommended, such as programmatic clean development mechanisms or targeted abatement subsidies

(de Gorter, 2009). Further, Klein et al. (2005) argue that, instead of developing and implementing specific mitigation and adaptation options, climate policy should facilitate such development and implementation as part of sectoral policies.

In reality, however, policies coexist and are set one at a time. The interaction of the various policies may not always promote the reduction of GHGs. The implications from coexisting policies have been extensively analyzed in a series of recent papers (de Gorter and Just, 2008, 2009a; Lapan and Moschini, 2009; among others). De Gorter and Just (2008, 2009a) showed that (1) fuel prices always decline with a biofuel consumption subsidy (a 'blender's tax credit' in the USA and tax exemption at the fuel pump in most other countries); (2) fuel prices may or may not decline with a mandate; and (3) with a mandate, a biofuel consumption subsidy subsidizes gasoline consumption instead. Lapan and Moschini (2009) argue that (1) biofuels mandates are equivalent to a combination of fuel taxes and biofuels subsidies that are revenue neutral, (2) biofuels mandates dominate biofuels subsidies and (3) combining fuel taxes (rather than subsidies) with mandates would be welfare enhancing. De Gorter and Just (2010) gave a comprehensive survey of the literature.

Land-use Change and Biofuels

A carbon tax would make biofuels more attractive, assuming that such fuels are associated with lower carbon emissions than fossil fuels. However, clean biofuels impose other costs on the environment. Because biofuel is a land-intensive technology, its production may lead to the destruction of natural habitats, including tropical forest. Consequently, unless nature is properly valued for the services it provides, including biodiversity preservation, carbon sequestration, water purification, waste assimilation and soil-erosion prevention, it will be converted to productive uses (e.g. food and fuel) at a rate that is too high relative to social optimality. Thus the social optimum solution suggests that a systematic and global mechanism for monetizing natural habitat should be set in place, such that the price of nature land equals the marginal social benefit from nature land.

Biodiversity preservation is both a local and global public good and, therefore, subject to free-rider problems and underprovision by landowners who do not appropriate the full benefits of their conservation effort (Perrings and Gadgil, 2003). Much of the biodiversity is embodied in tropical forest and, without intervention, will be exploited at a rate higher than is socially desirable.

Optimal land conversion can be achieved with a Pigouvian tax on the conversion of natural land to other uses, which recognizes heterogeneity in land values based on the biodiversity at stake and the potential to provide ecosystem services (Hochman et al., 2010). It should also account for heterogeneity in environmental impacts based on land use. Even within agricultural uses, for instance, there is significant variation in environmental impacts depending on which crops are grown (e.g. annual versus perennial crops) and which farm practices are adopted. While conventional tillage leads to carbon emissions, low-tillage methods lead to carbon sequestration. Pastureland frequently provides more environmental benefits relative to land planted to grow crops. In addition, the policy design must account for the appropriately discounted future benefits from natural land and the limitations of natural systems. Thus the derivation of taxes should recog-

nize the irreversibility of ecosystem damage (such as species extinction) and the fact that productive land can only be restored to natural habitat at a large cost.

An alternative instrument is the payment for environmental services (PES) in which the provider of the environmental services (e.g. reduction of GHG, biodiversity conservation) gets paid by the beneficiary of the services (Wu et al., 2001). One hypothetical form of PES is where landowners are paid to protect the tropical forest and not grow biofuels. Participation in PES is voluntary, and PES schemes may be supported by public agencies. Thus it generates new financing sources for conservation. The PES equilibrates the cost of a unit of emissions due to deforestation with the marginal externality cost of carbon emissions. Such payments would have the same efficiency implications as a land tax but would require government outlays to landowners who preserve their lands. More importantly, this mechanism is driven by self-interest of service users and providers. Biodiversity preservation could be achieved most effectively through payment for conserving natural habitat. However, biodiversity can also be protected indirectly through payments for other environmental services, such as carbon sequestration (Kiss, 2004). National initiatives that employ PES in water management include the Cauca Valley water user association in Colombia, FONAFIFO/Pagos por servicios ambientales (PSA) in Costa Rica, Pagos por servicios ambientales Hidrologicos (PSAH) in Mexico, CVG-Edelca payments for conservation of Rio Caroni, among many others. Zoning is another alternative instrument that can be employed to preserve nature land.

Pricing both carbon and land correctly while internalizing environmental externalities associated with biofuel production renders life-cycle analysis and the whole debate of indirect effects irrelevant (Hochman et al., 2010). In particular, creating a pricing mechanism that correctly reflects the social cost of GHG emissions and land use, and lets the market price the indirect effects, is a more promising path to take by practitioners.

Existing policy decisions and policy-making processes are contemplating if and how to include indirect effects, that is, the pecuniary externalities associated with indirect land effects (e.g. RFS2, LCFS, European Directive). Empirically, however, quantifying the indirect land-use effects is difficult because these effects have been very unstable over time and sometimes even vary in sign. In addition, the effects of commodity prices on deforestation have not been well documented.

Food Security and Biofuels

Increased demand for energy raises demand for biofuels, which, in turn, raises demand for land to produce energy crops (Abbott et al., 2008; Hochman et al., 2010). Currently, energy crops compete for land with food production, increasing the cost of food production. As a result of this linkage between food and energy markets, policies may be needed to protect food supplies in the event of food emergencies, such as that witnessed in 2008 (Tyner and Taheripour, 2008; Hochman et al., forthcoming).

Biofuel policies should be flexible and adjust to food-market conditions. Biofuel mandates and subsidies could be tied to food inventories in order to avert food crises. Wright (2008) showed that low inventories lead to price-increasing behaviors, such as export restrictions in producing countries, increased storage and speculative activity (see also Hochman et al., forthcoming). Inventories can be used to reduce variations in prices and prevent unanticipated shortages that result from weak harvests or from strong demand.

Tyner and Taheripour (2008) proposed that biofuel subsidies be tied to the price of oil in recognition of the increasing competitiveness of biofuels as oil prices rise. Subsidies would fall as oil prices rise. Likewise, biofuel subsidies and mandates could be reduced as food inventories decline. While providing increased protection against food crises, this would create a less certain market for biofuels and could slow capital investment and innovation. Hochman et al. (2008) showed that due to the inherent instability of agricultural markets and oil markets, the biofuel industry is a boom–bust industry.

Fuel Security and Biofuels

Fuel security plays an important role in promoting biofuels. That is apparent from the name of the major US biofuel policy – Energy Independence and Fuel Security Act of 2007. Furthermore, the work of Lapan and Moschini (2009), which analyzed the impacts of biofuel policies, suggests that biofuel policies are set to enhance fuel security and independence but not GHG reductions (see also de Gorter and Just, 2008). The importance of fuel security is apparent from other sources as well. For example, the Outer Continental Shelf Deep Water Royalty Relief Act of 1995 exempts oil companies from paying royalties on oil pumped at wells in deep water (Zilberman et al., 2010).

Although biofuels production can be traced back to the 1970s, its rebirth in the twenty-first century resulted in a much larger effect and can be associated with domestic policies in the USA and elsewhere (see Rajagopal and Zilberman, 2007). In 2005, Congress passed the Energy Policy Act that adopted gradually increasing mandates for biofuel production. By 2008, with the realization that all biofuels are not created equal, the RFS was amended to slow the mandated growth of conventional biofuels (i.e. corn ethanol) and adopted standards for advanced biofuels and cellulosic biofuels (i.e. second-generation biofuels). The former offer limited GHG savings relative to fossil fuel and compete most intensely with food production for land (Figure 12.3 – see p. 254).

The fuel excise tax credit for biofuels is an instrument used to help biofuels compete with fossil fuels. Most nations levy a tax on the consumption of gasoline and diesel, and a fuel tax reduction for biofuel aims to lower the cost of biofuel relative to gasoline or diesel. Biofuel tax policies across countries vary widely in the level of reduction, the cap on production subject to reduction and the sunset clause. For example, in the USA, the volumetric ethanol excise tax credit provides a fixed tax credit of \$0.45 per gallon of ethanol blended with motor gasoline (and \$1.01 per gallon for cellulosic ethanol). The level of exemption does not adjust to changes in oil prices and has no cap on production and no sunset clause.

However, Germany, which also has similar tax credits, has begun phasing out tax reductions for biodiesel, which started in 2006. In France and Italy, biofuel tax policies are being reviewed each year. Spain has granted a full excise tax exemption for biofuels until the end of 2012, amounting to €0.42 (US\$ 0.57) per liter for ethanol and €0.29 (US\$ 0.39) per liter for biodiesel (Kojima et al., 2007). A tax credit is a subsidy to the processor (some of which is passed on to the farmer) and, therefore, raises their surplus. It also has a negative impact on government revenues. The ability to use this instrument depends on the level of excise taxes levied on petroleum fuels. Countries with low levels of taxation are not in a position to provide adequate reduction. In countries where fuel taxes are high because they are primarily for revenue generation, a fuel tax reduction

will adversely affect the fiscal situation (Koplow, 2006; Kojima et al., 2007). Tax credits, which are invariant with changes in oil price and have no caps on production level or do not have a sunset clause, can result in a large increase in subsidy burden if there is a structural break resulting in higher oil prices or a large increase in biofuel production.

In a few countries, fossil fuels are taxed to tip the scale in favor of biomass as an energy source. For example in Finland and Sweden, taxation of oil has been in use since the 1970s as one of the means of reducing oil dependence. Finland is considered the first country to introduce a carbon-based tax in 1990 while Sweden introduced it in 1991. As a result of such taxes, biomass became less expensive than coal in 1991 in Sweden and in 1997 in Finland. The general carbon tax in 2002 in Finland was €17.2/tonne CO₂, except for natural gas where it was half of this, and in Sweden €70/tonne CO₂. Peat in Sweden is taxed only for its sulphur content at €4.4/tonne of peat (40 SEK) or about €1.7/MWh (15 SEK/MWh). Peat in Finland is subject to an energy tax of about €1.5/MWh (Bohlin, 1998; Ericsson et al., 2004).

Government policies have aimed to stimulate supply and demand for ethanol-powered vehicles through direct subsidies in the form of tax credits and indirectly through energy-efficient credits to manufacturers of automobiles. State and federal policies in the USA and Brazil have given preference to alternative fuel vehicles, including flex-fuel vehicles (FFV) that can run on ethanol-blended gasoline. In the USA, the Alternative Motor Fuels Act of 1998 has provided credits to automakers in meeting their Corporate Average Fuel Economy standards when they produced cars fueled by alternative fuels, including E85 (Leiby and Rubin, 2001). However, the credits are not contingent upon achieving any particular efficiency of operation or actual use of ethanol-blended gasoline. In Brazil, vehicle tax policies have been tinkered with to adjust the supply of vehicles in accordance with the supply of ethanol (Geller, 1985; Geller et al., 2004).

A vehicle tax credit has effects similar to the fuel tax credit. It stimulates demand for FFVs and has a negative impact on tax revenues from the government's perspective. While a policy that provides efficiency credits seems to have no apparent implications for government budget, it is in fact claimed that a number of US automobile manufacturers avoided penalties that they would have otherwise had to pay on inefficient fleets. Estimates suggest that automakers have, as a result of this dual-fuel vehicle loophole, avoided nearly \$1.6 billion in penalties for falling short of federal fuel-economy targets (MacKenzie et al., 2005). The ultimate impact of such a policy is that automakers avoid investments in fuel efficiency, and consumers spend more on transportation. A vehicle tax credit, similar to the large array of biofuel policies surveyed above and elsewhere, suggests that objectives guiding policy may not be reduction of GHGs. Nevertheless, the impact on GHG emissions should be evaluated and, because policies tend to be made piecemeal in the future as the implications from GHGs become clearer, we may observe the introduction of biofuel policies that provide further incentives to reduce the GHG impacts of biofuel. The LCFS may play this role if their use is expanded globally.

Policy for Biofuel and Agriculture R&D

Improvements in the productivity of biofuel processing and agricultural technologies can improve the environmental outcomes by reducing agricultural land use, carbon emission and water and chemical input use. The adoption of agricultural biotechnology (Sexton

and Zilberman, 2010) has increased the productivity of crops, such as corn and soybeans; contributed to lower food prices; and reduced the demand for land and thereby mitigating the loss of natural lands.

The tools of biotechnology have produced a first generation of genetically modified staple crops. Since transgenic crops were commercialized in the mid-1990s, yield gains have been observed from the USA to South Africa and from Argentina to China (Qaim and Zilberman, 2003; Thirtle et al., 2003; Ismael et al., 2001; Traxler et al., 2001; Marra et al., 2002). Increased productivity of food and feed is important in order to avert future food crises, but so too is improved productivity of biofuels. The first generation of biofuels has made clear the obstacles that must be overcome in order for biofuels to provide a real solution to global food, energy and environmental challenges. First, they will need to compete less intensely for staple food crops to avert future food crises. Second, biofuels will need to offer greater GHG emission reductions. And third, biofuels will need to be less land and water intensive to avoid negative impacts on food and global warming and to prevent the loss of biodiversity and the right to water.

Emerging plant science can convert cellulosic plants (such as pulp, switchgrass and *Miscanthus*) into liquid fuel, make use of agricultural residues and turn marginal land into productive land. It cannot yet scale up these processes in a commercially viable way. Cellulosic ethanol promises to resolve the most significant problems associated with existing biofuels. Whereas only 500 ethanol gallons of harvestable corn grains are extracted from each acre of corn grain, 1700 ethanol gallons of harvestable biomass is produced on each acre of *Miscanthus*. Thirteen hundred gallons of cellulosic ethanol can be produced from each acre of *Miscanthus*. Only 450 gallons of corn ethanol are yielded per acre of corn. Under a hypothetical scenario of 35 billion gallons of ethanol production, corn ethanol would demand one-quarter of all harvested cropland in the USA. *Miscanthus* would need less than one-tenth (Heaton et al., 2008). With dedicated energy crops that can be grown on marginal lands, the next generation of biofuels would permit the entire harvest of staple crops to be used for food and feed (Khanna, 2008).

Cellulosic ethanol can also overcome the challenge of biofuels to offer significant GHG emission reductions relative to fossil fuels. By utilizing a greater share of harvested plants, utilizing crops that produce more biomass per acre, reducing input intensity of feedstock production and increasing efficiency of depolymerization and fermentation, the next generation of biofuels can greatly reduce the carbon intensity of biofuel production. Corn ethanol emissions are, at best, 25 per cent below gasoline emissions, but *Miscanthus* emits 89 per cent less emissions. Corn stover, which uses the residue of corn food and feed production, causes only 18 per cent as much pollution as gasoline (Khanna, 2008).

R&D on biofuel technologies has the potential to increase productivity and reduce costs. However, since investments in R&D have public-good characteristics, the private sector is likely to underinvest in such ventures. Knowledge spillover, which makes it difficult for inventors to reap the full social benefits of their innovations, is one such characteristic. There is, consequently, little controversy among economists about the desirability of governmental support for R&D investments (Klette et al., 2000). Federal spending on biofuels R&D in the USA is estimated to have ranged between \$50 and \$100 million a year between 1978 and 1998 (Gielecki et al., 2001). Several governments of the European Union, including Germany, France and Sweden, continue to invest in

R&D in biofuels. Investment incentives such as grants, loans and loan guarantees, tax-related incentives (tax holidays, accelerated depreciation, tax reductions), for example, are being provided in almost all countries to biofuel refineries (Koplow, 2006; Kojima et al., 2007).

Multilateral Cooperation on the Environment

Pollution problems usually are contained within countries, and governments establish policies such as taxes, property rights and standards to regulate them. When, however, externalities are transnational or global, as is the case of GHGs, an international governance structure to establish and enforce policies is needed. That is the reason for international agreements or international conventions that establish mechanisms for sharing responsibilities for pollution reduction and coordinating policy among countries. Although a ton of carbon is a ton of carbon and so the price of carbon should not vary widely among emitter, one cannot simply disregard any distributional effects that may prevent countries from joining an international agreement on the environment and adhering to their commitment in the future. Differences in GDP, energy-sector infrastructure and growth prospective among nations affect their perspectives and preferences on GHG management, resulting in further difficulties in reaching an international agreement on the environment.

Differences among countries, in terms of endowments and technologies, can be addressed by employing a compensating mechanism. With respect to tradable permits, a compensation mechanism may include grandfathering rights and allocation of permits. Another compensation mechanism that should be further considered, especially with regard to land management and land-pricing practices, is PES, which can be used to prevent deforestation in tropical forests and induce carbon sequestration in developing countries. Compensation can also be obtained by linking environmental agreement with trade agreements although the cost will probably be less trade.

In addition to international differences, there are intersectoral differences that make the design of effective policies to consistently address GHG emissions in the urban agricultural sector, as well as the industrial sector, very challenging. The design of climate change policies requires integration of scientific and economic data and knowledge, and calls for interdisciplinary collaboration. One of the major topics of research on climate change should aim to address issues of irreversibility and uncertainty.

Transnational cooperation among countries aimed at reducing GHGs is needed. The much-needed environmental agreement should lead to international institutions that result in emissions reductions but limit the cost in terms of economic welfare.

DISCUSSION AND CONCLUDING REMARKS

The evolution of the biofuel sector and the policies that guided it illustrate some of the challenges of establishing policy to reduce GHG emissions. Although many expected the introduction of biofuels to result in less dependence on foreign oil and lower GHG emissions from fuel consumption, the actual effect of biofuels on GHGs depends on the feedstock used and the technology used to convert the feedstock to biofuels. If not

appropriately produced and processed, biofuels may actually result in an increase in GHGs.

First-generation biofuels are part of a strategy to lessen the dependence on foreign oil and reduce the status of crude oil from a commodity that is required to sustain our way of life to just another commodity. But biofuels can also become part of the solution to global warming because some biofuels can reduce the amount of fuel-related GHGs emitted to the atmosphere – in particular if we succeed in moving toward second-generation biofuels and/or reduce trade barriers that restrict international trade in sugarcane-based biofuels (a relatively clean first-generation biofuel). However, even if the technology matures, governments may still need to intervene in fuel markets and expedite the adoption of biofuels by fuel consumers (e.g. subsidize flex-fuel cars).

With respect to policy, we offer principles that should be followed. First, following the principle of targeting, policies should target as explicitly and narrowly as possible the sources of market failures. If emissions of automobiles cause external social costs, emissions should be taxed, not production of energy or a particular production or end-use technology. Second, policies should account for heterogeneity in costs and benefits of various energy technologies and natural habitats. Third, ‘market-opening’ policies, supporting development of new promising technologies and motivated by dynamic efficiency considerations, should be temporary and seek to support technologies that will eventually compete on their own in the market. Fourth, governments should support R&D activities to provide basic knowledge to develop new agricultural and biofuel technologies. The regulations of these technologies should be based on their social opportunity costs that incorporate present and future benefits, namely, performance relative to existing technologies. This may mean that, at times, we need to take some small risks to avoid bigger environmental and economic risks.

NOTES

1. The costs of production are computed assuming, that the price of inputs, including the feedstock, is fixed. Allowing the boundary of the analysis to change, as well as introducing different costs, will clearly result in different numbers.
2. Available at <http://www.eia.doe.gov/>.

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13 The present and future role for agricultural projects under the Clean Development Mechanism

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INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), agriculture accounted for an estimated 5.1 to 6.1 GtCO₂e in 2005, or roughly 12 per cent of global anthropogenic emissions of greenhouse gases. At the same time there is a consensus that agriculture's net contribution to global warming could be greatly reduced, since the sector also provides ample mitigation opportunities – enough to remove or sequester up to 1.6 GtCO₂e annually at relatively low carbon prices. Most opportunities identified to date involve the use of agricultural biomass to generate power or involve changes in how agricultural lands are used (Smith et al., 2007). Especially important for mitigation are efforts to restore carbon pools in soil on degraded land. This closely links mitigation in agriculture with development, since most agricultural land-use opportunities are in developing countries where agriculture is an important source of income for the poor. Moreover, projects that sequester carbon in soils also help to reverse declining soil fertility, a root cause of stagnant agricultural productivity in Africa.

Under the Kyoto Protocol, countries that have pledged to reduce their emissions of greenhouse gases can invest in mitigation projects located in developing countries as a way of fulfilling their treaty obligations. The framework for this type of project investment is the Clean Development Mechanism (CDM).

In this chapter we examine the types of agricultural projects currently financed under the CDM. We find that most projects have to do with agriculture as a source of bioenergy, and that few projects tap the mitigation potential associated with changing how agricultural lands are used. We explore why this is so. We look at the aspects of agricultural land-use projects that make them complex and costly to implement under current CDM rules. We also examine the origins of the current CDM institutions and look at the feasibility of changing CDM rules to provide greater scope for agricultural projects.

AGRICULTURE AND FORESTRY AS A POTENTIAL SOURCE OF MITIGATION

In 2007 the IPCC reviewed projections across a range of modeling efforts to assess potential sources of mitigation by sector (Barker et al., 2007). Table 13.1 summarizes the report's assessment of mitigation opportunities at US\$20 per tCO₂e.¹ Recalling that the CDM is meant to target low-cost abatement opportunities in developing countries, the assessment suggests that the opportunities are greatest in the building, industry and

Table 13.1 Estimated potential for GHG mitigation in 2030 by sector at or below \$20/tCO₂e

	Total	Developing countries
Agriculture	1.60	1.10
Forestry	1.25	1.05
Energy	1.90	0.80
Buildings	5.50	2.85
Transport	1.75	0.13
Other	1.50	0.97
Total	13.50	6.90

Note: Potential given in GtCO₂e per year. Mitigation from burning agricultural residue is attributed to sector in which the fuel use takes place. The IPCC estimates that mitigation opportunities for this class of project at 1.26 GtCO₂e per year.

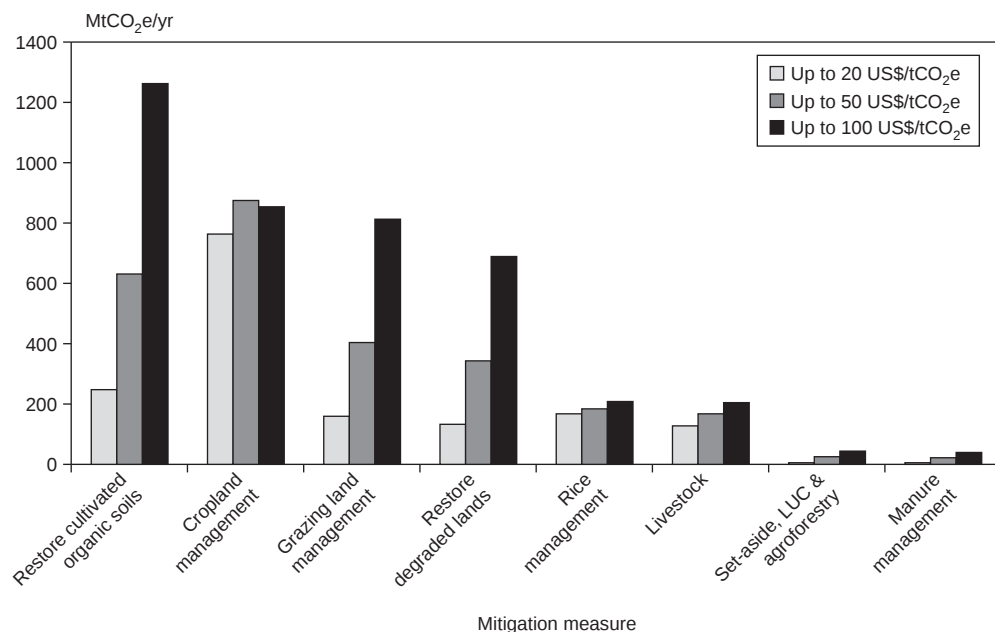
Source: Barker et al. (2007); Smith et al. (2007).

agricultural sectors. Moreover, the report concludes that most energy-saving efforts in the building sector would be profitable without additional carbon payments and are therefore ineligible for CDM crediting.² Consequently, modeling results imply that agricultural projects should feature prominently in the CDM.

As the more detailed chapter of the IPCC on agriculture makes clear, the consensus estimate of 1.6 GtCO₂e in mitigation potential is based on models in which the sector is narrowly defined, focusing on on-farm activities primarily involving crops and livestock and the handling of animal wastes (Smith et al., 2007). The authors note that, as a consequence, additional opportunities linked to the use of organic agricultural waste products, such as bagasse or rice husks, as a renewable fuel are not counted toward agriculture, but are attributed to sectors in which the fuel-switching takes place. Top-down studies referenced in the report suggest that this class of opportunities for mitigation is nearly as large as agriculture's on-farm potential, with mitigation estimates ranging from 0.7 to 1.26 GtCO₂e per year by 2030 at costs of US\$20 or below.

As Smith et al. (2008) emphasize, measuring the mitigation potential for agricultural land-use is complex because a single activity can initiate a chain of emission outcomes among a portfolio of greenhouse gases that also depend on local soils and local climate conditions. As an example, the authors cite evidence presented in Paustian et al. (2004) showing that composting manure can suppress methane emissions while simultaneously accelerating emissions of another greenhouse gas, nitrous oxide. Similarly, soil restoration can encourage carbon uptake in plants and soils, while stimulating the release of carbon through the decomposition of organic matter.

After accounting for interrelated effects, the authors provide a further breakdown of the mitigation potential for a set of agricultural activities under a range of carbon prices, shown in Figure 13.1. Keeping in mind that mitigation activities linked to agricultural biomass are excluded, the reported literature suggests that most mitigation opportunities are related to soil and land management practices that generate net sequestration gains. At low carbon prices (less than US\$20), cropland management practices are key sources



Note: The totals exclude bioenergy and improved energy efficiency.

Source: Smith et al. (2007).

Figure 13.1 *Potential for mitigation in agriculture at selected prices*

of mitigation, along with other land management practices, including the restoration of organic soils, degraded lands and improved management of grazing.

In the case of cropland management, improved agronomy is important, for example converting crop production from traditional to improved higher-yielding varieties. So is the use of chemical fertilizers, which can provide net emission benefits when soils are poor. This is true even though carbon is released in the production and transport of chemical fertilizers and nitrous oxide is generated when nitrogen fertilizers are used. Other productivity-enhancing activities identified in the report include the use of ground cover between perennial tree crops and the adoption of crop-rotation schemes involving nitrogen-fixing legumes. Better water management and the application of organic matter to cropland are also identified as activities that both enhance agricultural productivity and contribute to the restoration of organic soils on degraded lands. Important but smaller mitigation opportunities are tied to efforts designed to reduce methane emissions from wetland rice, livestock and manure.

Agricultural Projects under the CDM

We next turn our attention to the set of agricultural projects approved or waiting approval by the CDM board. The purpose is both to describe the flow of investments to agriculture under the CDM and to gauge the degree to which the mechanism has

been able to tap potential mitigation opportunities identified in the IPCC report. The first step in that process is settling on a definition, since the classification systems used by the IPCC in their mitigation reports and by the UN Risoe Center on Energy, Climate and Sustainable Development to report on CDM projects are not harmonized. Indeed, Risoe classifies only two projects as agricultural.³ Projects related to land use, the primary focus of the IPCC chapter on agriculture, are classified as afforestation/reforestation projects, which we refer to as land-use forestry projects.⁴ Other projects related to agriculture – for example systems to manage manure or projects that use agricultural waste products to generate energy – fall into other aggregate categories in the Risoe classification system, such as biomass energy or methane avoidance, which include non-agricultural projects as well. Consequently, for our purposes, we follow the lead of the UN Food and Agriculture Organization (FAO) and define an agricultural project as a project that uses agricultural residuals, outputs or agricultural processes to directly or indirectly reduce greenhouse gas emissions (FAO, 2010). This definition is broad enough to include projects that sequester carbon in soils. Like the IPCC, we do not classify biofuel projects as agricultural, but we do include projects in which residual agricultural organic matter is used to produce energy. We include projects that reduce methane emissions from composting agricultural waste products, but do not include wastewater projects, even though some wastewater is probably associated with processing agricultural products.

There are several stages in the CDM project cycle and projects can leave the project cycle at several points. For the purpose of this chapter, we focus on 5824 projects that were active as of 1 December 2010. The number of projects and their projected cumulative and average mitigation impacts by project type are given in Table 13.2. By our definition, about 17 per cent of the projects are classified as agricultural and land-use forestry projects, a category that includes mixed use agro-forestry projects and other projects that restore agricultural land, comprise another 1 per cent. In combination this is a significant share when compared to other categories, and only the hydro-power and alternative energy categories contain more projects. Based on Risoe's analysis of project documents, agricultural projects are expected to reduce business-as-usual emissions by nearly 220 mtCO₂e by 2012 and 582 mtCO₂e by 2020. In addition, land-use forestry projects are expected to account for another 17 mtCO₂e and 69 mtCO₂e respectively for the two periods. Even so, as the last two columns of the table indicate, agriculture projects and to a lesser degree land-use projects tend to be smaller scaled than other types of projects, so the mitigation impact shares are smaller than the project count shares.

The task of comparing the potential for mitigation identified by the IPCC and the expected level of mitigation from projects in the CDM pipeline requires a series of assumptions and extrapolation. For one, the modeling efforts behind the IPCC estimates envisage annual flows by 2030 under a set of certain prices and established markets. In contrast, the CDM market has been built from scratch and investments have been made under uncertainty. Moreover, project offset prices have stayed below US\$20 per ton since 2008, hovering mostly between \$10 and \$13 per ton. It is also worth pointing out that the CDM was never expected to finance the full set of mitigation opportunities in developing countries and that the CDM is in fact on track to exceed expectations (Rahman et al., 2010.) Still, the comparisons, though inexact, are

Table 13.2 CDM projects by type and expected mitigation impact by 2012 and 2020

Project type	Projects		Mitigation impact by 2012		Mitigation impact by 2020		Average project impact (ktCO ₂ e)	
	Number	share	ktCO ₂ e	share	ktCO ₂ e	share	2012	2020
Agriculture	964	0.17	219 507	0.08	582 081	0.07	228	604
Forests	58	0.01	16 638	0.01	69 109	0.01	287	1 192
Non-agriculture	1558	0.27	482 160	0.17	1 894 491	0.22	309	1 216
Hydro	1221	0.21	326 170	0.11	1 154 888	0.13	267	946
Alternative energy	837	0.14	332 619	0.12	1 139 571	0.13	397	1 361
Energy efficiency	340	0.06	191 296	0.07	596 638	0.07	563	1 755
Methane avoidance	326	0.06	204 097	0.07	537 122	0.06	626	1 648
Landfill gas	145	0.02	340 797	0.12	904 581	0.10	2350	6 238
Assorted gases	141	0.02	36 958	0.01	101 004	0.01	262	716
Biomass energy	133	0.02	191 523	0.07	585 274	0.07	1 440	4 401
Fossil fuel switch	44	0.01	35 444	0.01	76 590	0.01	806	1 741
Cement	34	0.01	10 157	0.00	39 160	0.00	299	1 152
Transport	23	0.00	476 541	0.17	1 100 353	0.13	20 719	47 841
HFCs								
Total	5824	1.00	2 863 906	1.00	8 780 862	1.00	492	1 508

Note: The non-agriculture categories are based on Risoe's classification system, net of those projects considered agricultural by the authors.

indicative since they give a sense of how effectively the CDM has tapped opportunities across sectors.

With this in mind, converting the total cumulative stock of offsets expected from the pipeline for the period 2008 to 2020 works out to an annual flow of about 675 mtCO₂e. Since the start of the CDM, the pace of projects entering the pipeline has increased and there are good reasons to expect this to continue if uncertainty over crediting after 2012 can be resolved. Still, the projected impact of pipeline projects represents less than 10 per cent of the potential 2030 flow of 6900 mtCO₂e of low-cost mitigation opportunities in developing countries identified by the IPCC.

Drawing a similar comparison about the gap between mitigation potential and the expected output from implemented projects is more difficult for agriculture. Part of this is conceptual and has to do with the already discussed differences between the modeling evaluations of what types of mitigation processes are agricultural and the classification system we use to categorize projects under the CDM. However, setting this aside, there is a practical problem in that the agricultural bioenergy estimates from the IPCC report do not identify the potential from developing countries separately. In general, the IPCC estimates that roughly 42 per cent of the mitigation opportunities in energy are in developing countries and, by that rubric, about 302.4 mtCO₂e of the agriculture-biomass potential should be in developing countries. Combining this with the potential from agriculture gives an estimate of about 1629 mtCO₂e. Generously combining the mitigation estimates for all 1022 projects associated with land use and agriculture provides a flow of just over 50 mtCO₂e, a bit more than 3 per cent of the IPCC total. Because we have included all reforestation and afforestation projects in the CDM total (regardless of whether they relate to the restoration of agricultural land), and because we have been generous in estimating the share of agricultural biomass potential attributed to developing countries, this already small share is most likely inflated.

A well-documented, if not anticipated, feature of the CDM is that a large portion of the projects are located in a handful of countries. The same holds true of agricultural projects. As shown in Table 13.3, China, India, Brazil, Mexico and Malaysia account for 78 per cent of all the CDM projects in our analysis, regardless of project type. Although there are minor differences in the ranking, the same five countries account for about 79 per cent of agriculture projects. Relatively few projects are located in Africa. However, this is not the case for forestry projects. Even though this category accounts for few projects, the projects are more broadly distributed across hosting countries, with a significant share of the projects in Africa.

Baseline Methodologies for Agricultural and Land-use Forestry Projects

Because the developing countries that host CDM projects do not limit overall emissions, project mitigation effects are measured against a business-as-usual counterfactual. In UNFCCC parlance, the way of assessing the net mitigation consequences of a particular project is known as a CDM methodology. The methodologies are detailed and specific to particular processes. For example, specific methodologies lay down procedures for measuring the impact of updating municipal heating systems or incinerating hydrofluorocarbons. New projects can use methodologies that have already been approved when appropriate; however, projects that introduce new methods or modify existing ones must

Table 13.3 Host countries ranked by the number of CDM projects hosted

Rank	All projects			Agricultural projects			Forestry projects		
	Host	Number	Cumulative share	Host	Number	Cumulative share	Host	Number	Cumulative share
1	China	2316	0.398	India	326	0.338	India	9	0.155
2	India	1549	0.664	Brazil	137	0.480	Kenya	8	0.293
3	Brazil	365	0.726	China	119	0.604	Uganda	6	0.397
4	Mexico	176	0.757	Mexico	104	0.712	Colombia	6	0.500
5	Malaysia	136	0.780	Malaysia	77	0.791	China	4	0.569
6	Vietnam	129	0.802	Philippines	53	0.846	Chile	3	0.621
7	Thailand	126	0.824	Indonesia	33	0.881	Congo DR	2	0.655
8	Indonesia	114	0.843	Thailand	27	0.909	Bolivia	2	0.690
9	South Korea	85	0.858	Chile	8	0.917	Moldova	2	0.724
10	Chile	77	0.871	Honduras	7	0.924	Brazil	2	0.759
11	Philippines	76	0.884	Sri Lanka	5	0.929	Ethiopia	1	0.776
12	Colombia	68	0.896	Ecuador	5	0.935	Ghana	1	0.793
13	Peru	40	0.903	Israel	5	0.940	Madagascar	1	0.810
14	South Africa	39	0.909	Colombia	5	0.945	Albania	1	0.828
15	Argentina	38	0.916	Nepal	4	0.949	Lao PDR	1	0.845
16	Israel	33	0.922	Cyprus	4	0.953	Paraguay	1	0.862
17	Honduras	31	0.927	Vietnam	4	0.957	Tanzania	1	0.879
18	Pakistan	25	0.931	Uruguay	3	0.961	Nicaragua	1	0.897
19	Ecuador	23	0.935	Morocco	3	0.964	Costa Rica	1	0.914
20	Sri Lanka	21	0.939	Kenya	3	0.967	Uruguay	1	0.931

Note: The full list of host countries is given in Appendix Table 13A.1.

Source: Risoe (2010) and authors' calculations.

have those methods approved by an expert committee before the project will be considered by the CDM board.

The methodologies used for the 1022 projects studied here are listed in Table 13.4.⁵ The projects rely on 33 approved methodologies, but the ten most frequently used methodologies account for 80 per cent of the projects. Often, more than one methodology is used in a given project. For example, a project might move organic material that would normally be left in the open to decompose into a contained area, capture methane released during decomposition, and use it to generate electricity. When requesting credit from the CDM board, project sponsors may use one methodology to account for the conversion of methane to less harmful carbon dioxide as the methane is burned, and another to calculate the benefits of displacing electricity produced with fossil fuels with electricity from a renewable resource.⁶

The fixed costs of bringing a project to the CDM board and the ongoing monitoring costs can be high, so to encourage small-scale projects, the CDM board distinguishes between small-scale and large-scale project methodologies. As can be seen in the table, agricultural and forestry projects contain a mix of small-scale and large-scale projects. Because of this, the methodologies that are most used are not strictly the same as those methodologies associated with high levels of expected mitigation.

Once approved, methodologies enter the public domain and can be used by subsequent project developers. For this reason, methodologies tend to follow a life cycle in which the use of the methodology increases as developers look for low-cost opportunities to replicate the methodology and then declines as replicable opportunities are more fully exploited (Table 13.5).

The methodologies exactly define the specific activities allowed under the CDM. Table 13.4 suggests that there are 33 actions associated with agriculture and forestry. However, a close look at the most widely used methodologies suggests that the methods are variations around a smaller set of core actions.

AMS-I.D is a methodology used to calculate the mitigation effects of displacing fossil fuels to generate electricity that enters a power grid from small-scale projects. ACM6 is a related consolidated methodology for larger-scale projects in which fossil fuels used to generate electricity and heat under the business-as-usual baseline are replaced by biomass residuals – for example, rice husks or the residual from crushed sugarcane. The methodology takes into account methane avoided by burning the residue rather than allowing it to decay. AMS-III.D is a methodology to account for recovering and burning methane in small-scale animal manure management systems. AMS.I.C is also a methodology based on burning biomass; however, it also can be applied to small projects that improve the efficiency of existing biomass projects – for example, the installation of equipment that improves the efficiency of thermal power components of a sugarcane crushing facility. AMS-III.F is another small-scale methodology based on the avoidance of methane emissions. In this case, methane emissions are avoided by composting organic material normally left in the open to decay, or by capturing biogas that is flared and potentially used to produce electricity. The methodology is often implemented at palm oil processing plants. ACM2 is a large-scale consolidated baseline methodology for grid-connected electricity generation from renewable sources. In the case of the projects studied here, it is most often used in connection with ACM6. AMS-III.E is another methodology based on the avoidance of methane produced from decay,

Table 13.4 Methodologies used for agriculture and forestry projects

Methodology	Number of projects	Mitigation (ktCO ₂ e)		Project scale	Mitigation action
		2012	2020		
AMS-I.D.	252	37 615	95 220	Small	Displacement of electricity produced by more GHG-intensive means
ACM6	191	71 139	206 925	Large	Renewable energy
AMS-III.D.	191	15 661	42 668	Small	GHG destruction
AMS-I.C.	187	27 259	77 867	Small	Displacement of more GHG-intensive thermal energy or heat
AMS-III.F.	48	4 757	14 635	Small	GHG destruction
ACM2	42	18 850	53 332	Large	Renewable energy
AMS-III.E.	28	12 790	32 279	Small	GHG emission avoidance
ACM3	26	11 120	28 032	Large	Fuel switch and renewable energy
AR-AMS1	23	773	6 213	Small	GHG removal by sinks
AMS-III.R.	18	2 226	9 314	Small	GHG destruction and fuel switching
AMS-III.H.	15	14 64	5 630	Small	GHG destruction
AM36	12	5 295	19 332	Large	Renewable energy
AM39	11	7 666	17 707	Large	GHG emission avoidance
ACM10	9	3 629	13 862	Large	GHG destruction
ACM18	8	2 450	13 381	Large	Renewable energy
AM25	7	1 389	4 994	Large	GHG emission avoidance, renewable energy
AMS-I.A.	7	650	1 885	Small	Displacement of more GHG-intensive service
AMS-I.E.	7	865	3 260	Small	Displacement of non-renewable biomass by renewable sources

AR-AM4	7	3701	12985	Large	GHG removal by sinks
AR-AM5	7	6436	28183	Large	GHG removal by sinks
AR-ACM2	4	1154	3183	Large	GHG removal by sinks
AR-AM3	4	632	1591	Large	GHG removal by sinks
AM73	3	870	3323	Large	GHG destruction
AMS-III.G.	3	684	1801	Small	GHG destruction
AMS-II.D.	2	47	183	Small	Energy efficiency
AR-AM2	2	1077	3314	Large	GHG removal by sinks
AM57	1	325	976	Large	GHG emission avoidance
AMS-II.F.	1	18	100	Small	Energy efficiency in agriculture
AMS-III.Q.	1	46	168	Small	Energy efficiency
AMS-III.Z.	1	134	413	Small	Energy efficiency, renewable energy, fuel switch
AR-AM10	1		3444	Large	GHG removal by sinks.
AR-AM9	1	236	657	Large	GHG removal by sinks
AR-AMS3	1	24	55	Small	GHG removal by sinks

Note: Because some projects employ more than one methodology, the number of methodology appearances exceeds the number of analyzed projects.

Source: Risoe (2010) and authors' calculations.

Table 13.5 Number of projects using selected methodologies by project start year

Methodology	2004	2005	2006	2007	2008	2009	2010	Total
ACM10	5	40	7	5	1	0	2	60
ACM2	0	6	8	4	14	7	3	42
ACM3	0	7	1	5	5	2	6	26
ACM6	3	35	51	22	54	34	21	220
AM36	0	1	0	1	3	5	2	12
AM39	0	0	0	8	1	2	0	11
AMS-I.C.	0	12	18	24	50	32	51	187
AMS-I.D.	2	47	63	51	31	29	29	252
AMS-III.D.	0	14	84	29	28	24	12	191
AMS-III.E.	0	2	12	4	4	2	4	28
AMS-III.F.	0	0	5	17	14	7	5	48
AMS-III.H.	0	0	0	0	5	2	8	15
AMS-III.R.	0	0	0	1	2	1	14	18
AR-AMS1	0	0	0	2	10	9	2	23
Other	0	2	5	9	20	7	26	69

Note: Because some projects employ more than one methodology, the number of methodology appearances exceeds the number of analyzed projects.

Source: Risoe (2010) and authors' calculations.

mostly through controlled burning or through gasification. ACM3 is a large-scale consolidated methodology based on the use of alternative fuels in the production of cement. In a few cases, the alternative fuel is based on agricultural residues, which is how the methodology came to be included in our study. Allowing for some double counting of projects that use multiple methods, these eight methodologies account for roughly 86 per cent of the projects and about 78 per cent of expected mitigation impact from the projects that we include in our study.

Among the remaining methodologies, five are significant for agricultural land use. The most used land-use methodology in our sample is AR-AMS1, a simplified baseline and monitoring methodology for planting trees on grasslands or cropland while maintaining most pre-project activities. This is significant, since some land-use methodologies prohibit continued grazing on lands covered by the project. AR-ACM2 is a related large-scale methodology, where pre-existing farming activities are continued after project implementation. AR-AM4 is a methodology based on planting trees and shrubs on degraded land that is used for agricultural purposes. AR-AM5 is a related methodology for commercial agricultural purposes. Land-use methodologies account for about 4 per cent of the study sample and about 8 per cent of expected mitigation.

Table 13.6 uses information from the methodologies to reclassify projects by a core set of activities. From the table, it is clear that more than 80 per cent of the projects and expected mitigation impact is associated with either using left-over agricultural matter (primarily rice husks, bagasse and oil palm husks), or the management of manure in a way that captures methane and converts it to less harmful carbon dioxide and

Table 13.6 CDM projects expected mitigation impact by core set of activities

	Number of projects	Expected mitigation (ktCO ₂ e)	
		2012	2020
Agricultural residues	615	153 768	428 634
Manure	288	52 837	119 486
Composting	60	12 883	33 861
Land use	57	16 614	69 054
Irrigation	1	18	100
Mangroves	1	24	55
Total	1 022	236 145	651 189

Source: Risoe (2010) and authors' calculations.

frequently energy as well. Afforestation, reforestation and composting projects account for most of the remaining projects. The remaining two projects are based on energy efficiency gains.⁷

PROJECT MARKETS OUTSIDE THE CDM

Not all projects designed to mitigate greenhouse gas emissions from agriculture operate under the UN Framework. Voluntary markets offer an alternative way of financing agricultural land-use projects. Overall, these markets are small relative to regulated markets, including the CDM (Table 13.7). However, they are significant and collectively finance a greater volume of offsets than Joint Implementation.⁸ Most voluntary market transactions originate in the USA, which is not a party to the Kyoto Protocol.⁹ Projects traded in voluntary markets are not subject to the same types of review and public disclosure that characterize the CDM market; however, the application of third-party standards is common. In their annual review of voluntary markets, Hamilton et al. (2010) estimated that over 90 per cent of voluntary transactions in 2008 and 2009 adhered to third-party standards, but also counted 18 competing standards active in voluntary markets.

In some cases, the types of projects financed by voluntary markets are similar to classes of projects eligible for financing under the CDM. For example, in 2009 landfill and wind projects accounted for 39 per cent of the offsets financed by voluntary markets (Hamilton et al., 2010). Still, investors have been attracted to the voluntary market as a way to invest in land-use projects that are difficult to finance or have been excluded from financing under the CDM.

An estimate of land-based credits financed through voluntary markets is reported in Table 13.8. Although the combined volumes of land-based projects in 2008 and 2009 were small, the projects collectively represented a significant share of the voluntary market. Nevertheless, among these, the portion of credits arising from agricultural land-use projects remained quite small, constituting 4 per cent of the voluntary market in 2009 and less than 1 per cent in 2008.

Table 13.7 Volume and value of project-based transactions, 2008–09

	2008		2009	
	Volume MtCO ₂ e	Value US\$ million	Volume MtCO ₂ e	Value US\$ million
CDM	404	6511	211	2678
Joint Implementation	25	367	26	354
Voluntary market	57	419	46	338
Total	486	7297	283	3370

Source: World Bank (2010).

Table 13.8 Land-based offsets traded on voluntary OTC markets

Project type	Volume (ktCO ₂ e)		Share of voluntary market (%)	
	2008	2009	2008	2009
Afforestation/reforestation	4091	4253	8.00	10.00
Avoided deforestation	730	2846	1.00	7.00
Forest management	431	1349	1.00	3.00
Agricultural soil	267	1250	0.50	3.00
Agro-forestry		625		1.00
Other land-based projects	130	109	0.03	0.03
Total	5649	10432	10.53	24.03

Source: Hamilton et al. (2010).

HURDLES TO INCLUDING AGRICULTURAL PROJECTS IN THE CDM

In the previous section we described the gap between the available mitigation opportunities in agricultural land-use projects and capital flows from the CDM and from voluntary markets. In this section, we examine specific design features of the CDM that work against land-use projects in general and discuss the origins of these features. We then explore how the practical concerns that gave rise to this structure also work to limit funding from markets outside of the Kyoto mechanisms.

The CDM is designed to facilitate capital flows to developing countries to tap low-cost mitigation opportunities and to promote sustainable development in countries that have not themselves pledged emission reductions. But this basic design tenet of the mechanism has vocal critics and support for the mechanism, even among some signatories of the Kyoto Protocol, has been equivocal. One consequence is a set of varied national policies and a complex set of international implementation rules that try to remediate concerns about the environmental efficacy of the CDM and its impact on development. Additionally and separate from the underlying questions that motivated their genesis,

the mechanism's implementation rules give the CDM a particular institutional structure that has practical consequences, influencing the type of mitigation efforts feasible in developing countries within the UNFCCC. For the most part, this structure works against the development of projects related to how land is used, and this, in turn, works to exclude the types of projects that would target the largest sources of low-cost mitigation opportunities within agricultural sectors. More generally, it also explains why the country and sector composition of the projects that now constitute the CDM project cycle pipeline differ from estimates of the sector distribution of low-cost mitigation opportunities discussed earlier.

Objections to the CDM and their Influence on its Design

The CDM, dubbed the 'Kyoto surprise', emerged late in the negotiations of the Kyoto Protocol and has been called the least loved of Kyoto's contentious flexibility mechanisms (Werksman, 1998). The mechanism was intended to address two divergent set of interests: a desire by developed countries to access low-cost mitigation opportunities in developing countries; and a need by developing countries for a new channel for development assistance (Grubb et al., 1999; Lecocq and Ambrosi, 2007). Moreover, for the mechanism to work, the difficult problem of finding a way to create environmentally sound credits in countries without pledged limits had to be solved.

Although the CDM was outlined in broad strokes in the 1997 Kyoto Protocol, the practical design of the mechanism was worked out in a protracted set of negotiations, which were not fully concluded until 2003. The rules that emerged partly reflected the early divergent views that had made negotiation over the mechanism so difficult. But they also reflected the difficult and technical challenges of designing and verifying project-based mitigation efforts when only one of the parties faces emission limits.¹⁰

Lecocq and Ambrosi (2007) identify four key areas of conflict that still shape the CDM: (i) tensions over the use of flexibility mechanisms in general; (ii) disagreement over the procedures for creating new credits under the CDM; (iii) tension over how to accommodate the twin objectives of mitigation and development under the CDM; and (iv) controversy over the consequences and permanency of forestry and other land-use projects.¹¹

Flexibility mechanisms

In the lead-up to the Kyoto Protocol, flexibility mechanisms were strongly opposed by several NGOs (non-governmental organizations) and some European negotiators, largely on normative grounds. For these groups, developed countries that contributed most to the accumulative of greenhouse gases over time were morally bound to redress the problem by acting within their own borders. Other groups went further, arguing that CDM would be exploitive and erode the authority of developing-country governments.¹²

In some cases, opposition to the flexibility mechanism may have been tactical. Negotiators had reached agreement on emission allocations before discussions on the flexibility mechanisms were complete. Consequently, groups already concerned that the aggregate supply of allowances had been set too high may have chosen to focus on limiting how allowances could be used or new allowances created rather than revisiting the allocation decision.

The value of using CDM offsets and other tradable permits to reduce the cost of mitigation was questioned on positive grounds as well, as some modeling work suggested that low carbon prices would reduce incentives for new innovative technologies and result in long-run welfare losses.¹³ The basic logic of the argument is that investments made when carbon prices are high are more likely to be associated with innovative technologies that generate positive externalities that, in turn, improve the productivity of other firms. Said differently, advocates maintained that innovation increases as the shadow price of capital devoted to mitigation increases – at least for a relevant set of carbon prices – and, over time, the benefits of improving the productivity of mitigation technologies exceed the initially high costs of abatement.

At Kyoto, negotiators divided into separate camps and a coalition led by the EU and Swiss delegations pushed to place quantitative limits on the use of tradable credits. Language emerged in the final draft of the Protocol stating that the flexibility mechanisms would be ‘supplemental’ to domestic actions, but, with the exception of forestry credits, quantitative restrictions were never imposed in subsequent rounds of rule making (Platjouw, 2009).¹⁴ Nevertheless, national governments have leeway in how the flexibility mechanisms can be used within their borders, and several countries have imposed quantitative restrictions.

In the case of the European Emission Trading Scheme (EU-ETS), the aggregate use of Kyoto units is limited to 13.36 per cent of the 2008–12 emission allocation; national rules vary. For example, Estonia forbids the use of Kyoto units, while Lithuania, Norway and Spain place a cap at 20 per cent (Larson et al., 2008).¹⁵ Moreover, in addition to general restrictions on CDM offsets, certified emission reductions (CERs) originating from land-use projects are completely excluded from the EU-ETS, which has additional implications for pricing and finance, a topic that we return to later.

Creating new credits

There was also great skepticism about project-based mitigation (Lecocq and Ambrosi, 2007). A core concern had to do with the idea of using a hypothetical business-as-usual counterfactual scenario to determine the number of credits earned by a particular project. Elements of the counterfactual cannot be observed and the full implications of the project are to a degree speculative, opening the evaluation process to strategic manipulation.

Conceptually, firms that face binding constraints under cap and trade or in the form of a carbon tax will undertake mitigation efforts to the degree that the costs are matched by the added revenue associated with additional emissions. Importantly, the firms make their own judgment about the efficacy of capital invested in mitigation. Outside of the cap, a different set of incentives is in place. Firms that fail to make mitigation efforts are not penalized, but can be induced to mitigate if it is profitable to do so. Indeed, this is the underlying essence of the CDM, since many low-cost mitigation opportunities are located in countries where greenhouse gas emissions are not regulated.

In this case, a judgment external to the firm must be made about how an investment affects emissions, and this leads to potential problems of information asymmetry. This is because firms both inside and outside of the cap stand to benefit from an exaggerated evaluation of an investment’s impact since they can share a larger number of credits. A related difficulty is that new investments often affect emissions and production costs

jointly. In this case, the private benefits from the investment (e.g. from energy efficiency gains) must be subtracted from the cost of the investment used in the mitigation calculations. This becomes especially complex for projects where host firms face restricted access to capital, since the cost of capital enters into the calculation of economic additionality.¹⁶

A final difficulty has to do with indirect 'leakages', that is, when a portion of the mitigation gains from a project are lost via general equilibrium effects. This can occur when actions taken by firms in the aggregate influence the set of relevant input and output prices, inducing a change in the behavior of others. As a consequence, a set of unexaggerated mitigation claims can be overvalued in the aggregate when the business-as-usual baseline analysis is performed on a firm-by-firm basis. Burniaux and Martins (2000), Barker et al. (2007), and Larson et al. (2008) provide reviews of the literature.

Because of the incentives for firms to exaggerate their mitigation claims and the technical challenges of fully accounting for the secondary effects of project investments, negotiators decided that environmental additionality would be tested on a project-by-project basis, rather than at a program level as some negotiators had proposed. Moreover, the review would be undertaken under the guidance of an independent executive board. This resulted in the current rules whereby the creation of credits requires both an initial approval of the baseline (counterfactual) methodology and monitoring methodology by the executive board, and a final certification of *ex post* evidence that the mitigation had occurred.

The development objective and bilateral approval

As negotiations proceeded, there were several calls for a mechanism that would provide developing countries with a stream of revenue that could be used to promote mitigation activities. Most notable was the 1997 'Brazilian proposal', which envisioned penalties for countries that exceeded their pledged emission targets to be paid into a clean development fund to support mitigation efforts in non-Annex I countries (Matsuo, 2003). As the negotiations progressed, the idea of a central fund managed under the UNFCCC gave way to the notion that individual projects would probably benefit developing countries by improving access to capital and by fostering technology transfer. Consequently, it was left to host countries to determine on a case-by-case basis whether an individual project contributed to the host country's development objectives.¹⁷

The decision resulted in a series of implementation protocols. For a project to go forward, project developers must obtain a letter of approval from the host-country government stating that the proposed CDM project activity contributes to sustainable development. Project developers must seek approval from the investor country as well, although it is only the host country that makes a determination of the project's developmental impact. To make this practical, each country designates a responsible agency (known as the designated national authority) to formally certify the project's contribution.

Not all designated authorities are equally efficient, so country-specific differences in transaction costs emerge. Moreover, not all host countries were equally prompt in establishing a designated authority. Both factors have probably influenced the skewed geographic distribution of projects discussed earlier.

Although the potential for the CDM to promote technology transfers motivated the mechanism's late inclusion in the Kyoto Protocol, no formal mandate merged. Still,

some project organizers claim to promote transfers in the documents they present to the executive board. Based on an examination of 854 early projects, Haites et al. (2006) found that 81 per cent of projects related to agriculture claim technology transfer. By way of comparison, only 41 per cent of wind-energy projects and 15 per cent of hydro projects in their sample claimed to have transferred technology.

Land management projects

Rule-making for sinks and land-use projects proved especially difficult. While most rules for the CDM were in place following conferences in Bonn and Marrakech in 2001, it was not until a final set of rule-making in 2003 that the full set of guidelines for land use, land-use change and forestry (LULUCF) projects emerged (Lecocq and Abrosi, 2007). The rules that did eventually emerge were cautious and restrictive, and placed strict limits on the creation of land-use credits, and special restrictions that distinguished land-use credits from the credits produced in other sectors.¹⁸

As discussed, land-use projects are technically complex since changes made to capture greenhouse gases can initially release carbon into the atmosphere. A full accounting of the type required for most CDM projects involves measuring the net change in carbon stocks for particular sites as well as any related increases in emissions off site, taking into account above-on and below-ground biomass and soil organic carbon. The projects are also long-lived and subject to reversibility because of human activity such as logging or natural events such as forest fires or disease. Consequently, many negotiators held deep reservations about whether the projects would deliver sound and permanent environmental benefits. Added to this was a concern that CDM market economics would favor projects based on fast-growing industrial plantations, crowding out projects that are community-based and that promote biodiversity (Hunt, 2008; Boyd, 2009).

In particular, current rules permit afforestation and reforestation projects but exclude projects designed to slow deforestation.¹⁹ Moreover, rules limit the total amount of land-use CERs that can be used to meet Kyoto obligations during the first commitment period to 5 per cent of their base-year emissions; Bernoux et al. (2002) estimate that this limits the market for CDM land-use credits to 11 MtCO₂e for the first commitment period.

To address reversibility, a new set of credits was created with a special set of rules. To start, net removals from the project are certified every five years. Project developers can choose between two types of CERs: long-term CERs (lCERs), which expire at the end of the project's crediting periods, or temporary CERs (tCERs), which expire at the end of the next commitment period. (For example, tCERs issued during the first commitment period would expire at the end of the second commitment period.) If the project performs as planned, new tCERs are issued to replace expiring ones until the end of the project's crediting period. However, Annex I countries that use tCERs during the first commitment period have to replace them during the next commitment period with so-called permanent credits (for example AAUs or CERs from non-LULUCF projects). The same restriction does not apply to the use of lCERs; however, if the accumulated stocks of stored carbon from a project for which lCERs have been issued declines during the five-year certifications, Annex II countries must replace a proportional share of the lCERs that they used. If a project fails to submit a certification report, all lCERs issued to the project must be replaced.

Consequences for pricing and profitability

Built to redress weaknesses related to business-as-usual counterfactuals, features of the CDM project cycle also influence a set of transaction costs that vary among types of projects. Because of this, the overall cost of operating a project under the CDM can be high even when abatement costs are themselves low. This is the case for agricultural land-use projects, where the design of the CDM, the complex biochemistry of soil carbon sequestration and the frequent need to coordinate the activities of many land users combine to inflate transactions costs. Moreover, many transaction costs are fixed and this works against small-scale projects in general, and smallholder and community-based projects in particular (Michaelowa et al., 2003; Skutsch, 2005).

Drawing on Dudek and Wiener (1996) and Cacho et al. (2005), Cahco and Lipper (2007) provide a topology of transaction costs for soil sequestration projects based on five categories: (i) search and negotiation; (ii) board approval; (iii) project management; (iv) monitoring; and (v) enforcement and insurance. Using this framework, the authors draw on published project reports for smallholder reforestation and afforestation projects to calculate project transaction costs by category. They find disparate results, with wide differences among projects across all categories. They report search and negotiation costs ranging from US\$22 000 to \$160 000; and approval costs from \$12 000 to \$120 000. Differences in monitoring costs were remarkable, ranging from \$5000 to \$270 000.²⁰

As discussed, the formal rules associated with implementing the CDM also work to limit demand. For example, limits on how CERs can be used under the EU-ETS prevent full arbitrage between the markets and consequently CDM credits trade at a discount to their European counterparts.²¹ The restriction spills into formal markets for price discovery and risk management as well; for example, CERs originating from land-use projects are excluded from the European Climate Exchange. Rules that exclude projects from the CDM also shift some projects to voluntary markets where credits trade at a steep discount to credits traded under the EU-ETS or the CDM. For example while all carbon prices fell dramatically in 2008 as global economic conditions worsened, spot prices for CDM offsets still remained above US\$15 tCO₂e for most of 2009. By comparison, the World Bank (2010) estimates that the price for voluntary credits averaged less than US\$5 per ton.

In addition, market sentiment disfavoring land-use projects appears to extend beyond the effects of the formal rules. Outside of the CDM, this is revealed in the voluntary markets where offsets from land-use projects sell at a discount to other types of mitigation projects. In their review, Hamilton et al. (2010) noted that all of the over-the-counter agricultural soil credits they tracked originated on the Chicago Climate Exchange and, in line with that market, traded for an average price of US\$1.20 per ton; forest carbon offsets sold for just under US\$3 per ton and afforestation and reforestation credits sold for just over US\$4 per ton, on average.

Evidence of revealed preferences for particular types of projects can be found within formal CDM markets as well, even though all types of tradable Kyoto offset units are notionally equivalent for the purpose of meeting treaty obligations. For example, 'State and trends of the carbon market' (World Bank, 2010) reports that owners of the most desirable renewable energy projects often bypass exchange platforms where no distinction is made among CERs by origin in order to obtain premiums of roughly €5 Euros per

CER. A similar price differentiation occurs via the private branding of CDM projects, as land-use projects are frequently ineligible for some well-known third-party certification programs, including Gold Standard certification (Gold Standard Foundation, 2010).

Taken together, the restrictions land-use projects face during the CDM cycle, the formal restrictions placed on their use by governments, their disfavor among buyers and higher transaction costs all work against the economic viability of land-use projects.

ANCILLARITY BENEFITS AND SUSTAINABLE RURAL DEVELOPMENT

For many, the limited scope for agricultural land-use projects under the CDM represents a missed opportunity to finance sustainable development. This argument rests on two foundations. The first has to do with the sector composition of current investment flows, already discussed in an earlier section. The notion here is that while the benefits of slowing climate change are especially important to the rural poor, the current composition of projects favors the energy sectors and manufacturing, and consequently has little impact on this generation of the rural poor.²² The second set of arguments, explored in the next section, has to do with the fundamental role played by soil carbon for agriculture and soil fertility management.

Soil Carbon Sequestration and Productivity

Especially in Africa, soil carbon sequestration is closely tied to agricultural productivity and consequently food security and reduced poverty. Vågen et al. (2005) note that soils are degraded on more than 3.5 million km² of land in sub-Saharan Africa and this accounts for roughly 20–25 per cent of land area. Of this, estimates suggest that 1.1 million km² is severely degraded. To make matters worse, Henao and Baanante (2006), reported in Morris et al. (2007), estimate that 85 per cent of African farmland suffers soil nutrient losses at a rate of 30 kg per year or greater. Especially in remote places, high transport and transaction costs push up the farm-gate price of chemical fertilizers and this encourages farming practices that further degrade the land and discourage the adoption of higher-yielding grain varieties.²³ Marshalling payments for the adoption of farming practices that reverse this downward cycle is seen as a strategic way of promoting sustainable agricultural practices (Antle and Diagana, 2003).

Numeric studies suggest that the ancillary productivity benefits of adopting carbon-sequestering farming practices that come via higher yields are the dominant source of welfare gains for farmers working degraded soils. This comes about because of a confluence of factors, primarily the price of carbon credits, the price of agricultural output, the sequestration capacity of the soils and monitoring costs. Using indicative numbers, Graff-Zivin and Lipper (2008) estimated that carbon-market-related returns associated with switching from traditional to carbon-sequestering conservation methods ranged from US\$0.90 to \$15 per hectare, amounts that are unlikely to motivate changes in farming practices. To emphasize their point, the authors reference a study set in Senegal (FAO, 2004) that estimated the returns from marketable soil carbon credits amounted to less than 4 per cent of household income. In contrast, productivity benefits are

Table 13.9 Carbon soil sequestration and net revenue gain under alternative farming practices

	No external inputs	Improved seeds	Improved seeds and fertilizer	Agroforestry
Carbon sequestration rate (tCO ₂ e)	0.5	1.0	1.5	4.0
Values (\$/ha)				
Annual carbon payments	1.15	4.90	8.65	27.40
Annual revenues from yield improvements	34	225	450	225
Total additional revenues	35	230	459	252
Seed costs	0	29	29	23
Fertilizer costs	0	0	60	0
Additional labor costs	45	68	90	75
Total additional costs	45	68	150	75
Net revenues	-10	162	309	177

Note: Carbon is priced at \$4.90 CO₂e, maize at \$0.15/kg.

Source: Tennigkeit et al. (2009).

often large. This is illustrated in Table 13.9. The table is constructed from a study by Tennigkeit et al. (2009) that looks at a stylized carbon sequestration problem for African maize on degraded soils under four farming practices. In all cases, the returns from improved yields exceed the gains from carbon credit sales.

Still, the juxtaposition of large ancillary benefits from adopting soil-sequestering farming methods and the widespread use of farming practices that degrade soils is part of a large puzzle of why farmers in developing countries fail to adopt more profitable and sustainable technologies (Larson and Plessmann, 2009). Hurdles to technology adoption include limited knowledge by farmers about the practices in combination with poor access to extension services. Limited access to credit can constrain technology adoption as well, since productive practices often require the up-front purchases of more costly seeds and fertilizers that poor farmers are unable to self-finance. Moreover, adopting new technologies can be risky since the higher up-front costs can magnify potential economic losses due to bad weather or poor output prices. Consequently, farmers may choose not to adopt improved technologies when formal and informal insurance markets are weak and they are unable to self-insure.

Many of the same hurdles apply to the decision to take up soil carbon sequestering technologies and often additional hurdles as well. Particularly in the case of conservation agriculture, changes in soil management practices lead to a change in the soil ecosystem; indeed, this is the underlying objective. However, during a transition stage in which the soil system moves from one equilibrium to another, vulnerabilities associated with weeds or soil-borne pests or pathogens shift, leading to greater uncertainty about yields (Hobbs, 2007; Graff-Zivin and Lipper, 2008). Consequently, the adoption of land management practices that can improve yields brings the same type of uncertainties that are associated with adopting new seed varieties or other innovative practices.

The limited empirical literature on the adoption of soil fertility management technologies is consistent with the general literature on smallholder technology adoption. In a study based on a survey of smallholder farmers in western Kenya, Marenya and Barrett (2007) report that resource constraints prevent farmers from adequately investing in soil fertility, even when their livelihoods depended crucially on agriculture. Moreover, many farmers in the study who tried using modern management techniques later dropped the practice. Dropout rates were particularly high for agro-forestry soil management techniques. A study by Odendo et al. (2009), which also uses data from Kenya, also found a negative relationship between resource constraints and investments in soils.

Problems that lead to land degradation in the first place often stand in the way of improved practices as well. Chief among these are tragedy-of-the-commons problems, where unfettered access results in the over-use of land resources through overgrazing or shifting agriculture. The related problem of weak property and tenure rights also discourages sustained investments in soil fertility. In both instances, farmers are not confident that they will be able to claim future productivity gains from current efforts. Potentially, both types of problems can be resolved in a project setting, but compensating for the absence of working formal or informal land institutions adds to the cost of the project and can introduce a high level of risk from coordination failures.²⁴

It is also worth mentioning that carbon sequestration can be an ancillary benefit of activities focused on other objectives. This is especially true of a group of actions designed to promote agricultural productivity in a sustainable way. For example, the development of farming approaches that conserve soil moisture or soil nutrients can create costs savings for farmers and deliver sequestration as well. Developing new high-yielding seeds that promote intensification can lead also to positive 'leakages' when, in the aggregate, this reduces the conversion of forests to farmland. Moreover, although a sharp distinction is made between mitigation and adaptation under the UNFCCC Framework, the distinctions become especially blurred in the case of land use. To continue the example above, the development of soil management technologies that conserve soil moisture and water resources also increase resilience to climate change. This implies an important role for government-supported agricultural research that has resource management and sustainability objectives in mind. A recent World Bank report (2010) points to Brazil's efforts in low-fertility Cerrados areas as an example of sponsored research that jointly promotes productivity, adaptation and mitigation.

Carbon sequestration and other environmental services

Although the link between soil carbon sequestration and soil fertility is emphasized, agriculture is associated with a wide range of externalities. As detailed by Lichtenberg (2002), agriculture is also a major contributor to environmental pollution through pesticides, fertilizers, animal wastes and sediment releases. While simultaneously affecting the environment, agriculture also depends on the environment. Agricultural productivity is enhanced by services provided by the natural environment, such as pollination, water supply and pest control. Agriculture may reciprocate by contributing to the stability or productivity of the natural environment, such as providing support for bird or insect populations.

Daily (1997), cited in Heal and Small (2002, p. 1347), lists the various ecosystem services, most if not all of which can also be attributed to agriculture. Some are better

measured than others and most of them are also interconnected.²⁵ These ecosystem services can be divided into four somewhat different types (MEA, 2005): (i) provisioning services, mainly associated with production of food, fiber, freshwater and hydro-power; (ii) regulating services, mainly associated with affecting environmental conditions that include flow regulation, recharge groundwater basins, water quality regulation, climate regulation, air quality and carbon sequestration; (iii) cultural services, mainly associated with recreation and ecotourism, aesthetic values, spiritual renewal, religious and cultural values; and (iv) supporting services, mainly associated with soil formation and fertility, photosynthesis, nutrient cycling and water cycling.

In some instances, positive externalities associated with farming practices can be used to earn a premium for an associated product – for example, coffee grown in a way that encourages biodiversity. Even so, there can be large disparities between what consumers are willing to pay and the notional values of the associated environmental service or the cost of providing it.²⁶ Efforts have been made to market carbon in a similar way and some third-party certifications focus on processes that safeguard the environmental integrity of the project credits. However, early evidence suggests that labels or certifications are of secondary importance for project credit pricing (Conte and Kotchen, 2009).

As Antle and Capalbo (2002) point out, many important phenomena in agriculture involve complex systems whose behavior is affected by the interactions of two or more subsystems. In turn, because ecosystem services are interwoven, policies that address only one particular service or a subset of services may lead to distortive outcomes. Said in a different way, because agriculture is a complex and interactive system, creating an incentive mechanism that pays for only one stream of natural resource services may lead to perverse and unexpected outcomes when the payments affect other services adversely. In the particular context of carbon sequestration, the modification of management practices changes the overall economic profitability of their business as well as the level of externality impact on the natural system (Antle and Capalbo, 2002; Pfaff et al., 2000). In some instances, the positive aspects of improving soil carbon complement other environmental services such as the provision of water resources. However, this is not guaranteed.

A generalization of the idea of paying for greenhouse gas mitigation is the idea of paying farmers or communities directly for undertaking a range of activities that safeguard environmental resources. For example, payments for environmental services (PES) have been used for protecting municipal water supplies in Colombia, Mexico, Ecuador and El Salvador (Pagiola et al., 2004). And in the case of Costa Rica, PES programs have been used to encourage carbon sequestration while simultaneously protecting watersheds, biodiversity and scenic beauty (Wunder et al., 2008).²⁷ The approach is attractive since conservation outcomes are rewarded directly. Moreover, it also provides a mechanism for harnessing revenue from dispersed beneficiaries to pay for local activities that generate positive externalities, which is itself an underlying motive of the CDM.

A case study of how carbon income incentives affect projects with multiple objectives is offered by Nelson and de Jong (2003) and Lövbrand et al. (2009); both papers discuss Scolel Té, a land-use agro-forestry sequestration project in Chiapas, Mexico established under a US-sponsored pilot project and part of the UNFCCC's Activities Implemented Jointly (AIJ) program.²⁸ The pilot featured a mix of community development and environmental objectives organized around a local trust fund (Fondo Bilclimatico), established in 1997 to broker carbon contracts between farmers and the voluntary

carbon market. Under the AIJ, carbon credits were not eligible for credit against future greenhouse gas reduction commitments, but long-lived programs were eligible for conversion under the CDM once it was established. An effort was made in 2002 to assess the project's eligibility for conversion. Although the project currently remains outside of the CDM, Lövbrand et al. (2009) argue that efforts to make the project viable under the CDM have resulted in a shift in emphasis away from the social and environmental objectives toward the provisioning of carbon sequestration.

As discussed, one of the problems with carbon sequestration projects has to do with the cost of coordinating actions among a large number of project participants. And one characteristic of PES systems is that they provide a shared mechanism for delivering payments for services. Shared organizational structures can be put to other uses as well. An example is Niger's Community Action plan, designed to organize local government to deliver services that promote development. In this case, the program promotes social protection, the build-up of local infrastructure, in addition to pilot soil conservation and afforestation projects (World Bank, 2010).

PATHS FORWARD

To summarize, there are substantive mitigation opportunities associated with agriculture, and the CDM has proven successful in funneling private capital into certain types of agricultural mitigation projects, primarily projects that convert organic waste products to energy and projects that limit methane emissions. However, large opportunities for mitigation remain related to land use that the CDM in its current form has not tapped. In this section, we look at how the CDM can be improved to partially redress current restraints. Even so, because the CDM is not intended to fund ancillary benefits separate from mitigation, it is likely that land-use projects will remain underfunded. We then discuss supplemental or alternative mechanisms, within or outside of the UNFCCC Framework.²⁹

Modifying the CDM

As discussed, uncertainties about the permanence of agricultural land-use sequestration have resulted in restrictions on how agricultural credits are created and how they are valued in the marketplace. In addition, project characteristics add to the cost of implementing land-use projects, even when underlying abatement costs are low. Still, there are several ways that the current implementation rules can be changed so that they might benefit from the substantial investment flows that the CDM has been able to harness for other sectors.

Perhaps the most promising area has to do with reducing the cost of evaluating and monitoring soil sequestration outcomes. To start, it is worth pointing out that all parties to the UNFCCC have, individually, already settled on or will soon settle on a methodology for calculating the amount of greenhouse gas sequestered by soils or released through changes in land use. This is because all parties to the Convention are expected to declare national greenhouse gas inventories. Moreover, Annex I countries are asked to submit annual inventory reports and have done so since 1996.³⁰ The reports have

economic significance, since they factor into determining the extent to which countries have met their treaty obligations.

Lokupitiya and Paustian (2006) describe the reporting process and review the methods. They conclude that methodologies used currently to account for soil carbon inventories in developing countries are weak, but they attribute this primarily to weak measurement networks and the consequent lack of location-specific activity data, problems that can be remedied through fundamental investments. Ringius (2002) and González-Estrada et al. (2008) report on the benefits and hurdles associated with soil sequestration projects in the context of sub-Saharan Africa; Soto-Pinto et al. (2010) describe field measurements for mixed land use in Chiapas, Mexico.

Finding reliable ways to calculate the impact of land-use practices on soil carbon sequestration that take into account local agroclimatic differences are also important for developing efficient policies. For example, in a study based on the USA, Antle et al. (2003) show that mitigation contracts based on per-ton sequestration incentives are five times more efficient than contracts that pay farmers to adopt soil conservation practices on a per-hectare basis.

All of this points to a need for site-specific measures of how agricultural land-use practices affect net greenhouse gas emissions. It also indicates the possibility that methodologies currently employed in developed countries to assess their compliance with pledged emission reductions can be used to quantify the net benefits of agricultural land-use projects in developing countries. To be practical, this would in turn require adjustments in the types of baseline methodologies accepted by the CDM board. Approaches put forth recently include a household multiple-criteria approach and related benchmarking techniques.³¹ A related idea is to allow trading of offsets within sectors. This has appeal, since a land-use offset created under the CDM would be matched with a land-use emission from a regulated market using a common methodology.

A second, somewhat technical, point is that there is some scope under current CDM rules for addressing some of the investment hurdles associated with land-use projects. One recognized tool for establishing baselines uses what the CDM board terms 'barrier analysis' (United Nations Environmental Programme Center Risoe, 2005). This step allows the project organizers to identify non-financial barriers that would prevent apparently economically viable investments from taking place outside of the CDM. This class of constraints can include risks associated with the technology, limits to credit and barriers that result from prevailing practices. First-of-kind project often benefit from barrier analysis, as do projects that are traditionally difficult to finance. Still, barrier analysis tends to be used to address the special circumstances of an individual project and may not be well suited to broad application as an integral part of frequently used methodologies.

Supplemental and Additional Mechanisms for Investing in Land-use Mitigation Projects

As discussed earlier, PES systems can be organized to reward multiple objectives, such as the preservation of biodiversity or the safeguarding of water supplies, and several examples of comprehensive systems were given in an earlier section. In this sense, land-use CDM projects can be viewed as a kind of PES system that pays for carbon sequestration, a particular type of environmental service. However, the funding of CDM

projects is organized differently, since the Kyoto Protocol creates incentives for private payments. In general, the same is not true for the ancillary services provided by land-use projects, and their financing is left to governments, international organizations and voluntary organizations. These sources are probably constrained, so land-use projects will be underfunded even if the private sector adequately funds sequestration. Fortunately, there are old and new mechanisms that could be harnessed to better fund agricultural land-use projects.

The first has to do with innovations in carbon funds. While it is difficult to find examples of mechanisms that leverage carbon revenue streams to finance the full set of benefits from land-use projects, several funds pursue multiple objectives linked to conservation and the promotion of sustainable agriculture and development. Examples include the BioCarbon Fund, the Community Development Carbon Fund, both managed by the World Bank, and the World Wildlife Fund's conservation and carbon finance projects.

In addition, multi-donor financing mechanisms have been established in recent years that can be used to supplement land-use mitigation activities. The largest and oldest is the Global Environmental Facility (GEF), a grant-making institution established in 1991 as a pilot project within the World Bank. The institution is now the financing instrument for the UNFCCC, as well as several other environmental conventions.³² Although the GEF climate program is diffused across capacity-building and adaptation programs, there is scope for mitigation activities and, in the case of agriculture, there is overlap with land management efforts designed to slow desertification that are also managed by the GEF.

In 2008, two climate investment funds were established under UNFCCC auspices.³³ The Clean Technology Fund is designed to speed up the transfer and deployment of low-carbon technologies in order to slow greenhouse gas emissions. The programs are designed and implemented by countries with assistance from the Regional Development Banks and the World Bank Group. Fourteen country and regional plans were endorsed through 2010, funding US\$4.4 billion in programs. Potentially, the fund could be tapped to address land-use mitigation efforts, although that has not yet occurred (World Bank, 2010).

The second fund, the Strategic Climate Fund, funds programs in three areas relevant for agriculture. The first is the Forest Investment Program (FIP), which is intended to support developing countries' efforts to stem deforestation and forest degradation. The program is also meant to build up experience in anticipation of REDD (reduced emissions from deforestation and degradation). The program funds efforts to encourage alternatives to extensive agricultural practices that can drive deforestation. A second Pilot Program for Climate Resilience (PPCR) is meant to integrate adaptation efforts into development planning and implementation. However, the program has relevance to our discussion because some adaptation activities also lead to mitigation outcomes. For example, the Niger program discussed above is partially financed by the PPCR (World Bank, 2010). The third window, Scaling up Renewable Energy Program (SREP), promotes renewable energy projects, including biomass energy pilots in rural areas.

Another potential source of financing is more recent. In the area of mitigation, Conference of Parties (COPs) in Copenhagen and Cancun have focused on voluntary steps that developing countries can take to slow emissions or improve sinks, and on new vehicles to finance those mitigation efforts.³⁴ As part of that process, developing countries

have been asked to submit a list of policies, programs and projects designed to mitigate domestic emissions, which are known as Nationally Appropriate Mitigation Actions (NAMAs). By the close of 2010, 44 countries had signaled their intention to undertake domestic mitigation in some form.³⁵ In the context of NAMAs, agriculture is a natural area of focus for many of the countries because of the links between land management, soil fertility and rural development. For example, in its NAMA, the Government of Ethiopia proposes projects that would add compost to agricultural lands and implement agro-forestry projects to improve rural livelihoods and sequester carbon in soils.

A related Green Climate Fund was introduced in Copenhagen and approved in Cancun that might provide direct funding to developing-country governments for adaptation and mitigation efforts under NAMAs. Another idea, introduced by the Government of New Zealand, would be to finance NAMAs using tradable credits similar to CERs (Macey, 2009).

CONCLUSIONS

Agricultural activities are an important and ubiquitous part of the ongoing build-up of atmospheric greenhouse gases, and they are also an abundant source of low-cost mitigation opportunities in developing countries. Currently, the CDM is the only formal channel by which countries that have pledged to reduce greenhouse gas emissions can invest in credit-earning mitigation projects in developing countries. The CDM has proved successful at mobilizing capital for mitigation projects and is on track to exceed initial expectations. Still, the sectoral and geographic distribution of projects has been narrow. Moreover, to the degree that model predictions of mitigation potential are a fair gauge, the CDM has not tapped deeply into the reserve of mitigation opportunities.

Within the agricultural sector, the CDM has been an effective conduit for mitigation projects that use residual agricultural organic matter as an alternative fuel source and projects that manage methane from composting and from manure. However, land-use projects that are designed to sequester carbon in soils face special problems under current rules. This is significant, since changing how land is used is an inexpensive way to slow the build-up of atmospheric carbon stocks, and because managing soil carbon stocks is important for agricultural productivity, especially in Africa where soils are badly degraded.

At the same time, addressing land use in a project context is difficult. The projects need to deal with the permanency of the mitigation they achieve in the short run and account for the cascading consequences of altering dynamic soil systems. Moreover, the degradation of lands often arises because of incomplete property rights and common use. As a consequence, reversing this type of degradation faces coordination hurdles, as effective management requires the participation of many stakeholders. Moreover, local conditions factor significantly in soil systems, so that the set of parameters used to establish net emission outcomes varies from place to place, making it difficult to replicate successful projects. All of this adds to steeper monitoring, measurement and implementation costs, making agricultural land-use projects less attractive to investors. Consequently, agricultural land-use projects, and especially soil carbon sequestration projects, are scarce, even in markets outside of the Kyoto Protocol where they face fewer restrictions.

Even so, the consequences of land-use changes are measured as part of the inventory-taking that parties to the UNFCCC are obligated to report. In addition, land-use changes affect carbon markets because they are part of the accounting that determines the demand of developed countries for CDM offsets. Because of this, considerable effort has been put into measurement methodologies, and these methods could be adapted for agricultural projects under the CDM. To the extent that parties to the UNFCCC are confident about the accuracy of the methodologies and to the extent that soil information networks are built up, this opens the door for including agricultural land-use projects under the CDM.

Still, doing so may leave investments in soils underfunded. This is because there are largely positive externalities associated with land-use projects. Well-thought-out and appropriately funded projects can generate ancillary benefits by protecting habitats and watersheds, and by contributing to food security and poverty reduction. Paying for the carbon component alone seldom provides the resources to generate all ancillary benefits. This leaves a role for communities and governments interested in sustainable agricultural development, biodiversity and other aspects of natural resource stewardship to fund the remaining investment gap.

NOTES

1. The Kyoto Protocol covers six gases: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). By convention, aggregate emission and mitigation amounts are expressed in terms of CO₂e, the amount of CO₂ needed to have the same global warming potential.
2. In CDM parlance, these projects lack 'economic additionality'; that is, under a business-as-usual scenario, firms would find investing in this type of energy saving profitable and do not face hurdles that would prevent them from doing so.
3. Both projects, only one of which remained active in 2010, reduced pump-well emissions by installing more efficiency drip irrigation systems.
4. In UNFCCC parlance, the class of mitigation projects that sequester carbon in soils and forests are known as land use, land-use change and forestry (LULUCF) projects, since the net mitigation comes from changing how land is used.
5. As the set of methodologies grows, similar methodologies are harmonized in a 'consolidated' methodology. In our classification, we use the most recent methodology designation; that is, we group each consolidated method with its respective antecedents.
6. Consequently, the sum of methods used exceeds the number of projects.
7. The irrigation project, set in India, saves fuel by using more intensive farming methods; the mangrove project, set in Cameroon, improves the efficiency of wood-burning stoves used in smokehouses, thereby reducing wood consumption.
8. Joint Implementation is a second project-based mechanism established by the Kyoto Protocol for projects based in countries that have pledged reductions.
9. Hamilton et al. (2010) estimate that 56 per cent of voluntary project transactions took place in the USA.
10. The mechanics of project-based mitigation had been explored prior to Kyoto in a series of national pilot programs known collectively as Activities Implemented Jointly, with mixed results. See Larson and Breustedt (2009) and references therein.
11. Briefly, the Kyoto Protocol, an international agreement linked to the UN Framework Convention on Climate Change, allows the developed and transition countries that have pledged to limit their greenhouse gas emissions (Annex II countries) during the first commitment period (2008–12) to meet their targets through domestic measures, or by acquiring three types of tradable offsets that represent reductions taken abroad. One type of tradable 'Kyoto units', Assigned Amount Units, is created when an Annex II country aggregate emissions fall below pledged levels. The other two types, emission reduction units and certified emission reduction (CERs) credits are project based, and stem from investments

in Annex II and non-Annex II countries (countries that have signed the Kyoto Protocol but have not pledged emission limits), respectively.

12. Harvey and Bush (1997) provide an early discussion of normative issues.
13. Conceptual and numerical models suggest that this construct holds under special circumstances. Arguments related to the long-term benefits, via induced innovation, of restricting emission trading are discussed in Matschoss and Welsch (2006) and Weber and Neuhoﬀ (2010). See Larson et al. (2008) for a review.
14. See in particular Articles 6, 12 and 17 of the Kyoto Protocol.
15. Operating since 2005, the EU-ETS mandates an overall limit or cap on carbon emissions that originate from large industrial facilities and electric power generating plants, and allows the trading of emission permits under the cap. The program affects firms in the EU's 27 member states, plus Iceland, Liechtenstein and Norway.
16. These questions have to do with economic additionality, the situation where the mitigation benefits exceed the private benefits of the investment. In so-called win-win projects, this is not the case.
17. Though separate from the CDM, special funds such provisions of the Global Environment Facility and the Clean Technology Fund have been established to assist mitigation eﬀorts in developing countries.
18. The fact that rules for LULUCF projects came late penalized this class of projects as well, since it left less time for the project to generate oﬀsets by 2012, the close of the first commitment period.
19. Reforestation is the restoration of depleted forests, while aﬀorestation is the conversion of other lands to forestlands.
20. The authors found that enforcement and insurance costs were largely unreported.
21. For example, the EUA-CER price spread ranged between €2 and 3 during the first nine months of 2010 (CDC Climate Research 2010).
22. See, for example, Sirohi (2007), who looks at the composition of CDM investments in India.
23. See Zerfu and Larson (2010) and references therein.
24. A counter-example is given in Minten et al. (2010), where good extension and well-defined property rights resulted in the adoption of new composting methods by smallholder farmers that improved productivity and soil fertility.
25. The list includes: control of the vast majority of potential agricultural pests; cycling and movement of nutrients; detoxification and decomposition of wastes; dispersal of seeds; generation and preservation of soils and renewal of their fertility; maintenance of biodiversity; mitigation of droughts and floods; moderation of weather extremes and their impacts; pollination of crops and natural vegetation; protection from the sun's harmful ultraviolet rays; protection of coastal shores from erosion by waves; provision of aesthetic beauty and intellectual stimulation that lift the human spirit; purification of air and water; stabilization of the climate.
26. See, for example, the discussion in Moon et al. (2002).
27. See also a comparative analysis of PES systems by Wunder et al. (2008) and a review of PES eﬀorts in Brazil's Amazonia by Hall (2008).
28. The AIJ program was a voluntary predecessor of the CDM, established as an umbrella framework for national voluntary mitigation pilot projects. See Larson and Breustedt (2009).
29. See a related discussion about institutional design and forestry projects by Forner et al. (2006).
30. The UNFCCC's inventory reporting requirements are described on its website, available at http://unfccc.int/national_reports/items/1408.php (downloaded 19 October 2010).
31. See González-Estrada et al. (2008). Anagnostopoulos et al. (2004) discuss benchmarking applications for CDM and JI energy projects.
32. Included are the Convention on Biological Diversity, the Stockholm Convention on Persistent Organic Pollutants, and the UN Convention to Combat Desertification.
33. The funds operate as trust funds administered by the World Bank. CIF stakeholders include the Multilateral Development Banks, UN and UN agencies, Global Environment Facility (GEF), UN Framework Convention on Climate Change (UNFCCC), Adaptation Fund, bilateral development agencies, non-governmental organizations, indigenous peoples, private sector entities, and scientific and technical experts.
34. Each year, the UNFCCC holds a meeting of its members, known as a Conference of the Parties (COP).
35. An updated list of NAMAs is available at www.unfccc.int/home/items/5265.php.

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APPENDIX A

Table 13A.1 Number of CDM projects hosted by country and share of total

Host country	Number of projects			Share of global total		
	All Sectors	Agriculture	Forest	All Sectors	Agriculture	Forest
China	2 316	119	4	0.398	0.123	0.069
India	1 549	326	9	0.266	0.338	0.155
Brazil	365	137	2	0.063	0.142	0.034
Mexico	176	104	0	0.030	0.108	0.000
Malaysia	136	77	0	0.023	0.080	0.000
Vietnam	129	4	1	0.022	0.004	0.017
Thailand	126	27	0	0.022	0.028	0.000
Indonesia	114	33	1	0.020	0.034	0.017
South Korea	85	0	0	0.015	0.000	0.000
Chile	77	8	3	0.013	0.008	0.052
Philippines	76	53	0	0.013	0.055	0.000
Colombia	68	5	6	0.012	0.005	0.103
Peru	40	2	1	0.007	0.002	0.017
South Africa	39	2	0	0.007	0.002	0.000
Argentina	38	3	1	0.007	0.003	0.017
Israel	33	5	0	0.006	0.005	0.000
Honduras	31	7	0	0.005	0.007	0.000
Pakistan	25	3	0	0.004	0.003	0.000
Ecuador	23	5	0	0.004	0.005	0.000
Sri Lanka	21	5	0	0.004	0.005	0.000
Guatemala	19	1	0	0.003	0.001	0.000
Panama	19	1	0	0.003	0.001	0.000
Kenya	18	3	8	0.003	0.003	0.138
Egypt	16	0	0	0.003	0.000	0.000
Morocco	16	3	0	0.003	0.003	0.000
Uzbekistan	15	0	0	0.003	0.000	0.000
Uganda	13	1	6	0.002	0.001	0.103
Uruguay	13	3	1	0.002	0.003	0.017
Armenia	12	1	0	0.002	0.001	0.000
Nigeria	10	0	0	0.002	0.000	0.000
Costa Rica	10	2	1	0.002	0.002	0.017
Dominican Republic	10	2	0	0.002	0.002	0.000
Cyprus	10	4	0	0.002	0.004	0.000
Moldova	9	0	2	0.002	0.000	0.034
Iran	9	0	0	0.002	0.000	0.000
United Arab Emirates	9	1	0	0.002	0.001	0.000
Nicaragua	8	1	1	0.001	0.001	0.017
Georgia	7	0	0	0.001	0.000	0.000
Cambodia	7	2	0	0.001	0.002	0.000
Tanzania	6	0	1	0.001	0.000	0.017

Table 13A.1 (continued)

Host country	Number of projects			Share of global total		
	All Sectors	Agriculture	Forest	All Sectors	Agriculture	Forest
Azerbaijan	6	0	0	0.001	0.000	0.000
Papua New Guinea	6	0	0	0.001	0.000	0.000
Bolivia	6	1	2	0.001	0.001	0.034
El Salvador	6	2	0	0.001	0.002	0.000
Nepal	6	4	0	0.001	0.004	0.000
Congo DR	5	0	2	0.001	0.000	0.034
Jordan	5	0	0	0.001	0.000	0.000
Singapore	5	2	0	0.001	0.002	0.000
Paraguay	4	0	1	0.001	0.000	0.017
Bangladesh	4	0	0	0.001	0.000	0.000
Cameroon	4	0	0	0.001	0.000	0.000
Mongolia	4	0	0	0.001	0.000	0.000
Rwanda	4	0	0	0.001	0.000	0.000
Syria	4	0	0	0.001	0.000	0.000
Tunisia	4	0	0	0.001	0.000	0.000
Lao PDR	4	1	1	0.001	0.001	0.017
Albania	3	0	1	0.001	0.000	0.017
Bhutan	3	0	0	0.001	0.000	0.000
Cuba	3	0	0	0.001	0.000	0.000
Côte d'Ivoire	3	0	0	0.001	0.000	0.000
Macedonia	3	0	0	0.001	0.000	0.000
Senegal	3	2	0	0.001	0.002	0.000
Madagascar	2	0	1	0.000	0.000	0.017
Fiji	2	0	0	0.000	0.000	0.000
Mauritius	2	0	0	0.000	0.000	0.000
Qatar	2	0	0	0.000	0.000	0.000
Sudan	2	0	0	0.000	0.000	0.000
Ethiopia	1	0	1	0.000	0.000	0.017
Ghana	1	0	1	0.000	0.000	0.017
Bahamas	1	0	0	0.000	0.000	0.000
Cape Verde	1	0	0	0.000	0.000	0.000
Jamaica	1	0	0	0.000	0.000	0.000
Lebanon	1	0	0	0.000	0.000	0.000
Lesotho	1	0	0	0.000	0.000	0.000
Liberia	1	0	0	0.000	0.000	0.000
Mali	1	0	0	0.000	0.000	0.000
Malta	1	0	0	0.000	0.000	0.000
Saudi Arabia	1	0	0	0.000	0.000	0.000
Serbia	1	0	0	0.000	0.000	0.000
Yemen	1	0	0	0.000	0.000	0.000
Zambia	1	0	0	0.000	0.000	0.000
Guyana	1	1	0	0.000	0.001	0.000

PART V

ADAPTATION TO AGRICULTURAL IMPACTS

14 Agricultural adaptation: needs, findings and effects

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INTRODUCTION

Adaptation to climate is a long-running characteristic of agriculture evidenced by the varying types and forms of agricultural enterprises associated with differing climatic conditions. Climate change, however, poses a substantial, additional adaptation challenge for agriculture (broadly defined here to include forestry) that will probably stimulate further shifts in location of production and processing, changes in management and altered research needs along with other influences (McCarl, 2007; Antle, 2009). Adaptation has been defined as an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects that moderates harm or exploits beneficial opportunities (IPCC WGI, 2001). Adaptation can be anticipatory or reactive, in addition to being planned or autonomous.

In this chapter, we review the agricultural adaptation issue in terms of (a) needs for adaptation; (b) ways people have adapted so far, and (c) the value of select adaptations. To do this we primarily rely on the literature but at the end present some quantitative results on the economic value of various strategies.

THE INEVITABILITY OF ADAPTATION

A substantial degree of climate change appears inevitable. Efforts to limit greenhouse gas (GHG) emissions are emerging slowly, while emissions continue to rise rapidly. Furthermore, it appears that given projected socioeconomic growth and lags in shifting the energy system, it is almost certain that emissions will continue to grow, causing substantial climate change. Moreover, even if net emissions fell to zero it would take a substantial time for the climate and atmospheric system to reach equilibrium. The IPCC WGI (2007) report contains projections indicating that if concentrations stabilize at 2000 levels, then global average temperature would increase by 0.3 to 0.9 °C in 2090–99 relative to 1980–99. As a consequence, it will be a considerable time before the atmospheric GHG concentration stabilizes or drops, and concentrations are likely to reach a high level causing considerable realized climate change (IPCC WGIII, 2007). Thus we feel the need for agricultural adaptation is inevitable (as argued in Rose and McCarl, 2008).

What Might be Adapted to: Climate Change Drivers and Effects on Agriculture

Climate change drivers that affect agriculture can be roughly grouped into six categories:

- temperature alterations that directly affect crop growth rates, livestock performance and appetite, pest incidence, plant evapotranspiration, soil moisture and reservoir evaporation, among other influences;
- precipitation alterations that directly affect the water available to crops, the drought stress crops are placed under, the supply of forage for animals, irrigation water supplies, river flows supporting barge transport and pest populations, among other items;
- changes in atmospheric CO₂ as it influences the growth of plants by altering the basic fuel for photosynthesis as well as the water that plants need as they grow. It also alters the growth rates of weeds;
- extreme events as they influence production conditions, destroy trees or crops, drown livestock, yield extended droughts, alter water supplies and influence waterborne transport and ports;
- sea-level rise as it influences the suitability of ports, waterborne transport and inundates producing lands;
- climate-change-motivated GHGs net emissions reduction efforts as they would influence the desirability of production processes and the costs of inputs plus add new opportunities to, for example, provide alternative sources of energy through expansions in biofuels or wind energy.

Agriculture will need to adapt to these forces. IPCC WGII (2001) identified six determinants that will influence the degree of adaptation: economic resources; technology availability; information and skills; infrastructure; institutions; and equity. Also relevant are degree of realized climate change, the amount of public and private investment undertaken, asset obsolescence, generated research findings, information availability and producer flexibility. As climate change becomes more apparent, laws and regulations that affect agriculture's ability to adapt may also change. The implementation of the GHG cap-and-trade policy, for instance, although currently stalled in the USA, has the potential to enable alternative energy sources among other implications and could indisputably have an impact on agricultural adaptation.

There are vast differences around the world in the availability of the aforementioned factors. For example, in the agricultural arena, differences can be observed in investment rates in agricultural technology research and diffusion despite a large need in terms of fundamental food supply (Pardey et al., 2006a; Pardy et al., 2006b; Roseboom, 2004).

IS ADAPTATION ALREADY OCCURRING?

Agricultural adaptive management is fundamental and ongoing, potentially contributing to sustaining the livelihood of millions of people worldwide. Examples in this regard are:

- crop production and the climate it faces vary substantially from year to year with, for example, the US total corn production varying by 20–30 percent. This requires adaptations that are manifest in harvesting, fertilization, pest control, irrigation and other management practices;

- beef production practices vary substantially from year to year with locally adequate sources of feed in some years and the need for large quantities of imported feed in others, with consequent management alterations in diet composition and animal-selling practices and/or regional migration;
- forests are at much greater risk of fire in some years than others, with adjustments possible through management and prevention practices;
- pest populations become resistant to treatment practices, with pest treatment practices managed to slow growth of resistance and adapt as resistance emerges;
- farmers have increasingly engaged in water markets as non-agricultural water scarcity has emerged;
- income and health concerns have shifted dietary preferences, with agriculture adapting in terms of livestock species composition and feeding practices;
- increased energy cost and falling water tables have caused many farmers to adapt by using water conserving technologies;
- changing commodity prices and climate conditions have led to northern expansions in corn and other crop production;
- nomadic activities among livestock owners have increased, especially in African countries bordering the Sahara desert as drier and harsher climates have emerged.

As inherent in the above examples, sectoral management regularly adapts to:

- long-run forces such as development of pest resistance to treatment methods; development of irrigation facilities; invasive species; consumer diet preferences; income effects on dietary choices; competition for water from municipal and industrial forces; early onset of climate change and changes in government policies among numerous other forces;
- short-run forces such as pest and disease outbreaks, El Niño–Southern Oscillation events, drought cycles and extreme event cycles among numerous other forces.

ADAPTATION ACTIVITIES AND ROLES

The influence of the climate change drivers above include the adaptation possibilities that

- climate-change-induced reduction in crop and livestock yields and altered yield growth rates may cause alterations in crop and livestock mixes;
- research investment needs would be increasingly devoted to adaptation so as to maintain productivity at a site as opposed to strictly increasing productivity;
- investments in capital-intensive agricultural practices may need to spread to new locations. Certain management strategies that need to be enhanced to deal with a rise in temperature and/or decreased rainfall may also be energy intensive and incur higher energy prices;
- relocation of processing and transport facilities may occur as a reaction to migrating cropping and livestock patterns;

- extension activities may need to expand to include educational outreach and dissemination of adaptation strategies;
- some currently productive areas might be marginalized, thereby requiring broader economic adaptations; other areas may be under pressure to expand agriculture with consequences of conversion of natural areas or greater pressure on other environmental resources.

These challenges are likely to be greater for developing countries where agriculture may be more susceptible to temperature and other climate changes, and where there is a lack of institutions to support adaptation. They will also place increased demands on producers, agricultural research, extension and infrastructure (McCarl, 2007; Antle, 2009; McCarl et al., 2010).

Some of the basic forms of adaptation and activities pursued within these structures are presented in Figure 14.1 (see p. 255). Climate change is expected to change price signals besides the yield effects, hence managers carrying out these adjustments indirectly respond to climate-induced price changes.

Activities to facilitate mitigation of climate change or adaptation to changing climatic conditions can be undertaken by different parties at different levels of operation and take diverse forms, the characteristics of which have implications for investment needs. Many of these adaptation possibilities would proceed without need for direct capital investment but several would require some mix of capital and research investments, with almost all requiring information and technology dissemination. How much agriculture will need to adapt depends on the level of mitigation, anticipated potential local climate change, capacity to adapt and relative impacts on other regions (Rose and McCarl, 2008).

MAGNITUDE OF ADAPTATION COSTS

As outlined in Parry et al. (2009), several groups have endeavored to estimate the magnitude of needed costs (Oxfam, 2007; Stern, 2006; UNDP, 2007; UNFCCC, 2007; World Bank, 2006), with the UNFCCC focusing on this most directly including an agricultural estimate developed by McCarl (2007). Parry et al. (2009) reviewed these studies and have further developed the cost estimate but concluded that these estimates are probably undervalued and that much more study is needed.

Unfortunately these costs are quite difficult to estimate, as is the ability of regions to implement them due to the reasons listed in Parry et al. (2009) and IPCC WGII (2001):

- adaptive capacity in terms of human and physical capital as well as resource base varies among regions and countries;
- uncertainty about the link between investment and adaptation;
- competing investment needs for food supply increases in support of growth and economic development versus adaptation;
- non-exclusiveness – adaptations are typically not to climate change alone, with other environmental matters, food needs, pest evolution and other factors contributing. Unraveling the climate change component is virtually impossible.

To illustrate the magnitude of such costs we briefly review the investment cost estimates generated by McCarl (2007), which indicate that global agriculture, forestry and fisheries investment in research, extension and infrastructure needs to

- increase in total by 47.2 percent by 2030 to match the no-climate-change baseline caused by one-third more people. This amounts to US\$520 billion or \$260 in 2030 per new person;
- increase by an added US\$12.9 billion without GHG mitigation to adapt to anticipated climate change;
- increase by an added US\$11.3 billion when GHG emissions are mitigated to adapt to climate change, considered relative to the no climate change baseline.

It is also worth pointing out that the magnitude of these investments is large compared to the value of climate impacts and may turn some of the positive ‘with adaptation’ findings (such as that in McCarl, 2006) to negative after considering the cost of developing and adopting adaptation (IPCC WGII, 2007).

The cost of adaptation in developing countries is expected to be higher than studies have shown because of the limited capital, research and extension funding, investment in infrastructure and institutional capacity. These factors (among others) needed to bridge the ‘development deficit’ greatly impact the ability of developing countries to adapt to climate change compared with high-income countries (Parry et al., 2009; McCarl, 2007).

APPROACHES TO AND FINDINGS FROM QUANTITATIVE ANALYSES OF ADAPTATION

Adaptation investigations in an agricultural context have taken on several different forms. Generally these are investigations based on

- observed data looking at the types of adaptation observed as climate varies;
- biophysical simulators looking at how management options influence performance under climate change;
- economic models that allow adaptation by including alternative production possibilities. Substantial economic modeling of other adaptation aspects such as the opportunity costs of public funds channeled into adaptation research has not appeared in the adaptation literature, and will not be discussed in this section.

Each will be reviewed below, with principal findings mentioned.

Adaptation Based on Observed Behavior

Adaptation behavior has been examined by looking at the way that observed farming practices vary over space and time, with climate conditions using a spatial-analogue approach. The basic assumption is that one gains insight into how agriculture might adapt to climatic variations in a region by examining the ways certain factors vary over alternative locations with varying climatic conditions (Chen and McCarl, 2001; Seo

and Mendelsohn, 2008a, 2008b; Seo et al., 2009a; Seo et al., 2009b). A large number of studies based on real-world observations have used this approach and some that have suggested items related to adaptation include

- Mendelsohn and Dinar (2003), who argue that observed behavior in Brazil and India shows smaller observed yield changes under climate change than agronomic results suggest, indicating that adaptation is present and effective;
- Chen and McCarl (2001), who find increased pesticide costs incurred as climate warms, indicating adaptation to climate-induced increased pest populations;
- Seo and Mendelsohn (2008b, c), who find that the mix of animals grown in Africa is climate sensitive, with farmers adapting the livestock species that they raise in accordance with the climate they face (also see Seo et al., 2009a and Seo et al., 2009b). They also find an effect on crop choice (Seo and Mendelsohn 2008a);
- Seo et al. (2009a, b), who find that total livestock population increases as temperature and rainfall increase, but that the population declines when the weather is too wet. Further, they find a conversion from crops to livestock as temperature increases;
- Mu and McCarl (2011) who find that climate change influences choice of livestock species and allocation of land between pasture and crops and stocking rates;
- Tubiello et al. (2000), who find currently that there are adaptations of varieties and planting times that avoid drought and heat stress during the hotter and drier summer months in Italy. Furthermore, they estimate that these adaptations have avoided significant negative impacts on sorghum (−48 to −58 percent), moderating them to neutral and even marginally increasing positive impacts (0 to +12 percent);
- IPCC WGII (2007) finds from a review of evidence on the benefits of adaptation that adaptation can provide approximately a 10 percent yield benefit when compared with yields without adaptation, but that these benefits vary with crops and across regions;
- other spatial and temporal examinations, while not explicitly examining adaptations, argue that their underlying models incorporate the effects of full farmers' adaptation (Deschenes and Greenstone, 2007; McCarl et al., 2008; Dixon and Segerson, 1999; Mendelsohn et al., 1994; Schlenker et al., 2005, 2006).

Adaptation Modeling – Alternative Management

A wide range of potential adaptations exists within agricultural systems that would help maintain or increase crop yields under climate change. Studies have been performed largely on cropping system management regarding the value of altered planting dates, harvest dates, varieties and so forth (e.g. Adams et al., 1995; Adams et al., 1999a; Easterling et al., 1993; Tubiello et al., 2000).

The US National Assessment study (Reilly et al., 2001a; Tubiello et al., 2002) examined a fairly comprehensive adaptation set using crop models to test the effects of early planting, cultivars better adapted to warmer climates and irrigation strategies. These results indicate that crop yield reductions can be reduced or increases enhanced by adopting adaptation strategies.

Other findings that emerge are as follows:

- Howden et al. (2007) argue that marine fishery adaptation is limited, except for management changes in catch size and efforts. However, it is possible that most fishing communities have developed coping capacity in accordance with fluctuating stocks caused by annual and decadal climatic variability (Brander, 2005; IPCC WGII, 2007; King, 2005);
- many studies have discussed the necessity of adaptation in water management systems but have not fully appraised the cost or feasibility of the adaptation options (Hayhoe et al., 2004; Hurd et al., 2004; Mote et al., 2003; Roy et al., 2001);
- adaptive strategies to deal with climate change are beginning to be considered in conservation of ecosystems (Chopra et al., 2005; Lemieux and Scott, 2005) and have emphasized the importance of planning guided by future climate scenarios (IPCC WGII, 2007);
- Porter and Gawith (1999) and Wheeler et al. (2000) argue that variability in climate can have important and dramatic impacts on the productivity of cropping systems meriting additional adaptation efforts.

Adaptation – Economic Modeling

Economic decision-making models have been used to simulate possible adaptations. This approach typically starts with climate change sensitivity estimates from field or individual plant-level crop simulation models as well as estimates on livestock sensitivity and irrigation water supply from other models or experts. In turn, the estimated effects are incorporated as shifts in the production possibilities in an economic, possibly agricultural sector, model which also contains adaptation options through changes in acreage, livestock numbers, livestock feeding, commodity supply, international trade and activity calendars. The economic models simulate behavior that seeks to maximize net farm income or, in national analyses, consumers' and producers' welfare (for an example see McCarl, 2006). This approach has been applied to look at adaptation at the state (Kaiser et al., 1993), regional (Easterling et al., 1993) and national levels (Adams et al., 1995; Adams et al., 1998; Adams et al., 1999b; Adams et al., 1988; Adams et al., 1990; Butt et al., 2005; Butt et al., 2006; McCarl, 1999, 2006; Reilly et al., 2001a). In this case adaptation can only employ possibilities portrayed in the model, so it is important to have an augmented set of production possibilities that can be used in the face of climate change. A challenge is to identify and incorporate the range of adaptations that farmers might employ. This is further complicated given that innovations continue to arise as induced by price changes, and the fact that most studies have yet to incorporate the costs of investments in alternative strategies.

A number of findings have arisen from such studies:

- Adams et al. (1998) looking the impacts of adaptations to climate change (among other objectives) looking at varietal–planting date–harvest date adaptations along with trade, crop mix, irrigation and consumption. Their results indicate that adaptations to climate change can play an important role in mitigating adverse effects of climate change;

- crop mixes and management practices have been found to shift in adjustment to direct and indirect climate change impacts (e.g. northward migrations in crop mixes, or altered pest management regimes as discussed in Adams et al., 1998, Adams et al., 1999a or Reilly et al., 2001b);
- adaptation can in certain cases switch yield and income effects from negative to positive in addition to greatly reducing the risk of hunger effects (Adams et al., 1995; Adams et al., 1999a; Butt et al., 2005; Butt et al., 2006; Easterling et al., 1993; Fischer et al., 2005; Kaiser et al., 1993; Reilly et al., 2001a);
- Butt et al. (2006) examined adaptation through crop mix, international trade and technology (in the form of adapted crop varieties) in Mali, showing that up to 38 percent of the negative effects on welfare could be avoided;
- producers in low–mid-latitude forests have been found capable of adapting with more productive short rotation plantings, driving down timber prices (Shugart et al., 2003; Sohngen et al., 2001; Spittlehouse and Stewart, 2003; Weih, 2004).

ECONOMIC VALUE OF SELECTED AGRICULTURAL ADAPTATION STRATEGIES

A small empirical study on the value of various types of adaptations following Adams et al. (1998) and Butt et al. (2006) was conducted.

Model Setup

To develop empirical estimates we used the agricultural component of Forest and Agricultural Sector Optimization Model (FASOM; see Adams et al., 2005) to investigate climate change impacts on the US crop–livestock sector with and without selected adaptation strategies. The specific adaptation strategies studied were:

- shifts in crop varieties and planting schedules;
- altered management practices such as irrigation water use;
- a 200-mile northward migration of crop mixes.

FASOM simulates the allocation of land over time to competing uses in the forest and agricultural sectors in the USA in addition to export markets, providing estimates of consequences for the markets of commodities supplied by these lands (Adams et al., 2005). Outcomes resulting from both climate change and market forces are expected.

Following McCarl (2006), four GCM projections were employed: specifically, the Hadley and Canadian scenarios used in the US Global Climatic Change Research Program (USGCRP) US National Assessment (Reilly et al., 2003; Reilly et al., 2001a; Reilly et al., 2001b) as well as the CSIRO and REGCM (Mearns et al., 2003) scenarios utilized in this study.

As summarized in McCarl (2006), the Hadley and Canadian scenarios falls in the middle and high end, respectively, of the 1996 IPCC projections of warming by the

Table 14.1 Scenarios run

	GCM used	MGT	MIX
Base	None	none	none
cc_no_adapt	Canadian	none	none
hc_no_adapt	Hadley	none	none
regcm_no_adapt	REGCM	none	none
csiro_no_adapt	CSIRO	none	none
cc_adapt_crop	Canadian	yes	none
hc_adapt_crop	Hadley	yes	none
regcm_adapt_crop	REGCM	yes	none
csiro_adapt_crop	CSIRO	yes	none
cc_adapt_full	Canadian	yes	yes
hc_adapt_full	Hadley	yes	yes
regcm_adapt_full	REGCM	yes	yes
csiro_adapt_full	CSIRO	yes	yes

year 2100; the CSIRO model performs a reasonably good simulation of present-day climate over North America compared to other GCMs available (Mearns et al., 2003); and the REGCM model has the advantage of greater regional detail. The US National Assessment data on climate change effects (McCarl, 1999; Reilly et al., 2001a; Reilly et al., 2001b) were used and included climate change effects on crop yield, irrigated crop water use, irrigation water supply, livestock productivity, grazing/pasture supply, grazing land usage, international trade and pesticide usage. Adaptations in the cropping system are considered using data of adaptation-adjusted performances simulated by crop models (Reilly et al., 2001b; Tubiello et al., 2000; Tubiello et al., 2002). The specific scenarios run for this study are listed in Table 14.1.

As detailed in Table 14.1, under the base scenario, no climate change occurs. In scenarios without adaptation, water availability, yield rates, livestock performance and other factors change, while in scenarios with adaptation, the yields and irrigation water use as well as the planting time, harvest time and varieties are adaptation adjusted. Notice that the term 'MGT' refers to the crop management strategies mentioned earlier and the term 'MIX' refers to the 200-mile northward movement.

Results and Implications

In the results detailed in this section, the term 'market forces' refers to autonomous socioeconomic adjustments. 'Physical' or planned adaptation encompasses cropping management timing and varietal adaptations (MGT) and crop mix migration (MIX) with 'Subtotal' as a sum of values added from 'physical' adaptations. MGT is separated from MIX to highlight the contribution of both adaptation opportunities.

Welfare

Table 14.2 depicts the changes in aggregate welfare for all scenarios relative to the base. Interestingly, climate change is beneficial even without planned adaptation. The value of

Table 14.2 Aggregate welfare changes in billions of US\$2004 for 2030

GCM	Human Market force	Physical			Total
		MGT	MIX	Subtotal	
Canadian	8.24	3.35	0.52	3.87	12.11
Hadley	12.47	2.89	0.89	3.78	16.25
REGCM	1.70	1.47	0.91	2.38	4.09
CSIRO	1.13	1.44	1.06	2.50	3.62

Table 14.3 Crop production changes in Fisher index (base = 100) for 2030

GCM	Human Market forces	Physical			Total
		MGT	MIX	Subtotal	
Canadian	6.63	6.06	0.69	6.75	13.37
Hadley	12.15	3.64	-0.29	3.35	15.51
REGCM	5.26	1.87	1.02	2.88	8.14
CSIRO	5.70	1.14	1.21	2.36	8.05

adaptations is significant, especially in the Canadian and Hadley GCM scenarios, with welfare increasing by up to \$16 billion in the latter. Autonomous adaptation can generate more than twice the value that MGT and MIX create together in some scenarios. In addition, irrespective of the scenarios examined, MGT contributions outweigh those of MIX. Also significant is the \$12.47 billion increase due solely to socioeconomic adjustment, which is over 75 percent of the grand total of value-added welfare for the Hadley scenario. Finally, it is important to note that there might be important implications for intertemporal as for well as interregional income distribution that would require research and planning, regardless of the path climate change follows.

Production

Relative to the base scenario, in Table 14.3, crop production for all scenarios is higher when human and the subtotal of physical adaptation are taken into account independently and jointly. Except for the Canadian scenario, all others show about twice the return for physical adaptation as for human adaptation. Crop varieties, planting schedules and management regimes are important determinants of production and these items are contained within the MGT, which explains the higher percentage of increase associated with MGT when compared to the MIX type of adaptation. Adaptation gains are pronounced but it is worth noting that the cost of investments required to adopt certain adaptation practices is not included.

For livestock production, as shown in Table 14.4, REGCM and CSIRO scenarios show slight increases with MIX and MGT adaptation but decreased output relative to the base overall as well as without 'physical' adaptation. For the other two scenarios (Canadian and Hadley), only MIX demonstrates minor losses in production. However, in all scenarios, MGT and total physical adaptation show some, albeit insignificant, increases. Adaptation showing even greater initial losses can be explained by the pos-

Table 14.4 Livestock production changes in Fisher index (base = 100) for 2030

GCM	Human Market forces	Physical			Total
		MGT	MIX	Subtotal	
Canadian	0.70	1.26	-0.19	1.07	1.76
Hadley	1.65	0.45	-0.01	0.44	2.10
REGCM	-1.11	0.28	0.07	0.35	-0.76
CSIRO	-1.14	0.25	0.00	0.25	-0.89

Table 14.5 Crop exports changes in Fisher Index (base = 100) for 2030

GCM	Human Market force	Physical			Total
		MGT	MIX	Subtotal	
Canadian	11.03	7.88	1.75	9.64	20.67
Hadley	15.04	5.14	1.23	6.37	21.41
REGCM	2.60	3.45	3.39	6.84	9.45
CSIRO	3.12	2.14	3.76	5.90	9.02

sible start-up costs and/or investments required in adopting certain adaptation practices. Beyond the investment phase, nevertheless, evidence of returns to adaptation could become apparent through marked increase in production.

Exports

Finally, Table 14.5 demonstrates that climate change with or without adaptation supports an increase in crop exports, with physical adaptation resulting in greater gains for REGCM and CSIRO scenarios than autonomous adaptation. This possible expansion could lead to a higher comparative advantage and increased income from international trade for the USA, especially with up to a 20 percent increase. International trade in itself has been shown to be a climate change adaptation option for many countries, but this alternative has not been explored in this study.

RESEARCH NEEDS

The range of possible climate change adaptations as well as the elements of climate change that stimulate adaptation raise a variety of research needs, including the following. Studies are needed that

- include the cost of adaptation in economic evaluations, as well as work on practical adaptation potential (IPCC WGII, 2007);
- consider strategies to deal with climate change for unmanaged or passively managed production systems;
- deal with resource and funds competition for food, energy, adaptation and mitigation;

- address burden sharing with respect to adaptation investment;
- examine means of adaptation to altered variability and the effects thereof. Parry et al. (2009) argue that this is a big challenge;
- examine the uneven distribution of climate change effects across the world and over time, developing localized and time-specific adaptation strategies;
- examine adaptation costs and possible diminishing marginal returns;
- address optimal degrees of adaptation and practical levels of the extent to which climate change vulnerability can be addressed;
- develop understanding of the process in which adaptation is taking place and will occur in the future (IPCC WGII, 2007);
- address means for adapting existing crops and livestock, move varieties of heat-tolerant crops and livestock breeds into regions and alter management (McCarl, 2007; Antle, 2009);
- examine levels of investment needed to insure a sufficient food supply given the factor productivity implications of climate change as found by McCarl et al. (2009).

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15 Hydro-economic modeling to assess climate impact and adaptation for agriculture in California

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INTRODUCTION

Dry–warm forms of climate change may significantly change water availability and agricultural yields and revenues in many parts of the world by the mid-century. Growing populations will demand more water and, in addition, urban footprint and environmental requirements may impose additional pressures on agricultural water uses. Counteracting factors such as technological improvements and price increases in some agricultural commodities may partially compensate losses to climate change and competing uses. In this chapter, we present and further discuss results from previous studies (Medellín-Azuara et al., in press) on adaptation of agriculture to climate change by mid-century in the midst of growing competing uses and technological change. We use irrigated agriculture in California as our case study. Previous studies on yield change suggest that various forms of climate change may severely affect most crops in California’s Central Valley (Adams et al., 2003; Lobell et al., 2007; Schlenker et al., 2005).

We employ the Statewide Agricultural Production (SWAP, <http://swap.ucdavis.edu>) model, a hydro-economic model for agricultural production in California. SWAP (Howitt et al., 2001) uses positive mathematical programming (Howitt, 1995), which is a deductive method that self-calibrates a base case to observed values of production factors use. Climate warming, technological change and urban footprint changes are introduced to contrast an unchanged historical climate, and to project climate change by 2050 with the 2005 base case for agricultural production. Water deliveries under both historical climate and climate change from larger hydro-economic models using CALVIN (<http://cee.engr.ucdavis.edu/calvin>) (Draper et al., 2003) were used to estimate shortages in SWAP.

In the next sections we discuss the methods and the model. Data sets and a base case for agricultural production in selected regions are presented for year 2005. Population and technological change by year 2050 are then introduced into the model to study agricultural production adaptation with and without climate change. Discussion of results and policy implications close this chapter.

HYDRO-ECONOMIC MODELING AND POSITIVE MATHEMATICAL PROGRAMMING

Hydro-economic Modeling

Hydro-economic modeling research began in the 1960s and 1970s with Bear and Levin (1970), who first used economic water demand functions to drive water allocation in an inter-tied regional water resources system (Harou et al., 2009). Hydro-economic models provide a framework to represent economically driven regional water resources systems. Usually the objective is to maximize total net benefits or to minimize total scarcity and operating costs in a network. Harou et al. (2009) provide a comprehensive review of hydro-economic models concepts and their applications.

The CALVIN Model

Hydro-economic modeling is undertaken in the present chapter within the CALVIN modeling framework. CALVIN is an economic-engineering optimization model of California developed at the University of California, Davis. CALVIN's major innovations are its statewide (rather than project) scale, representation of a broad range of water management options, explicit integration of broad economic objectives and its consequent applicability to a wide variety of policy, operations and planning problems.

Agricultural and urban water target demands by year 2050 cover more than 85 per cent of the projected irrigated agriculture and population, respectively. Both water demands are economically represented as loss functions on water scarcity. Scarcity or shortage is the difference between target demands and the economically driven water deliveries, and has a cost associated in the form of a convex piece-wise linear function. The SWAP model provides economic cost of water shortages for all agricultural demand locations in CALVIN (Howitt et al., 2001). Likewise, urban water demands are represented as loss functions for residential, commercial and industrial uses following Jenkins et al. (2003). To link output from SWAP, a loss function is obtained by numerical integration of the derived water demand, as illustrated in Figure 15.1. The green area in the figure is employed to generate loss functions for water scarcity, which have a value of zero at target delivery, and a positive value equal to the green area at water delivery less than the target deliveries.

The CALVIN model uses a 72-year monthly time series of hydrology (1921–93) to represent system variability. CALVIN manages water infrastructure and demands throughout California's inter-tied water network to minimize net scarcity and operating costs statewide. The model employs the Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM), a generalized linear network flow optimization solver developed by the US Army Corps of Engineers (Draper et al., 2003). A comprehensive review of CALVIN applications is presented in Lund et al. (2009) within the framework of the California Water Plan Update 2009.

The SWAP Model and Positive Mathematical Programming

The SWAP model, originally developed as an ancillary model to CALVIN (Howitt et al., 2001), continues to be improved, and has been used in multiple applications including

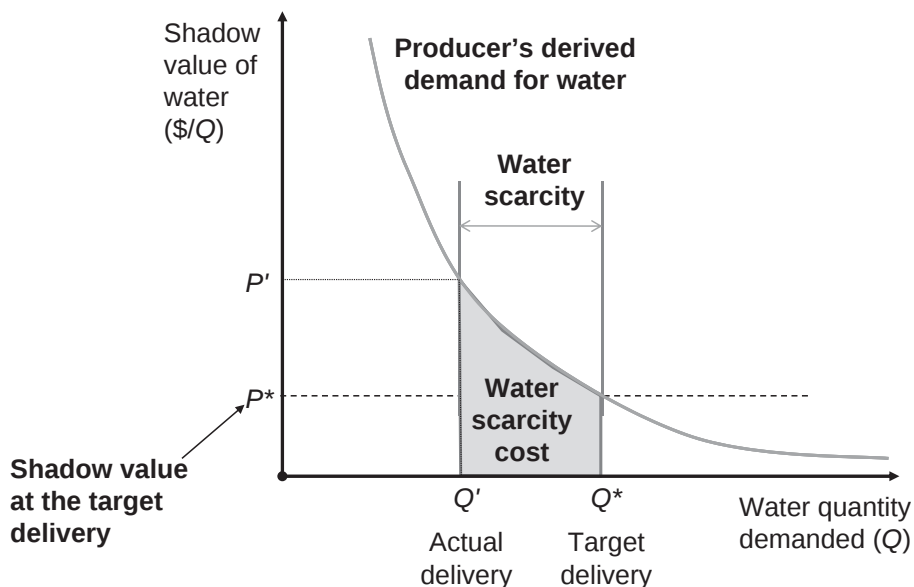


Figure 15.1 Water scarcity and water scarcity cost to generate loss functions

economic impacts of salinity in the Central Valley (Howitt et al., 2009a; Medellín-Azuara et al., 2008b) and Sacramento–San Joaquin Delta (Lund et al., 2007), and the impact of water shortages for agriculture on employment (Howitt et al., 2009b).

Positive mathematical programming (PMP; Howitt, 1995) is the underlying modeling framework of SWAP, and is a self-calibrating deductive three-step procedure to represent agricultural production. Farmers are assumed to follow a profit-maximizing behavior for a group of crops within a region, with land and water as the limiting constraints.

The first step in PMP starts with the linear program described by equations (15.1) to (15.3) below:

$$\text{Max}_{x \geq 0} \Pi = \sum_g \sum_i \left(v_{gi} yld_{gi} - \sum_j \omega_{gij} a_{gij} \right) x_{gi,land} \quad (15.1)$$

$$\sum_i a_{gij} x_{gij} \leq b_{gj} \quad \forall g, j \quad (15.2)$$

$$x_{gi,land} \leq \tilde{x}_{gi,land} + \epsilon \quad \forall g, i \quad (15.3)$$

The first equation is the objective function of a linear program. Decision variables are defined as follows: $x_{gi,land}$ is the total acres planted for region or group g and crop i . The marginal revenue per ton of crop i in region g is given by v_{gi} and average yields are given by yld_{gi} . Average variable costs, are used in the linear objective function 2. The Leontieff coefficients, a_{gij} , are given by the ratio of total factor usage to land. The second and third equations represent the constraint sets, equation (15.2) is for limiting resources (usually, land and water) and equation (15.3) is for calibration on land. The perturbation term, ϵ , is used to decouple the resource constraints.

A PMP exponential cost function (equation 15.4) is parameterized using ordinary least squares in a second step, with restrictions, on the PMP formulation and elasticity of supply for each crop group. δ_{gi} and γ_{gi} are the intercept and the elasticity parameter for the exponential acreage response function, respectively. Lagrange multipliers on the calibration constraint set are also used and a constant elasticity of substitution production function (15.5) is parameterized as detailed in Medellín-Azuara (2006).

$$TC_{gij}(x_{gij}) = \delta_{gi} e^{\gamma_{gi} x_{gi,land}} \quad (15.4)$$

$$Y_{gi} = \tau_{gi} \left[\sum_j \beta_{gij} X_{gij}^{\rho_{ij}} \right]^{\nu/\rho_i} \quad (15.5)$$

In the third and last step, a non-linear program is specified using the exponential cost function (15.4) and the parameterized production function in the following program.

$$\text{Max}_{x \geq 0} \Pi = \sum_g \sum_i yred_{gi} \nu_{gi} Y_{gi} - \sum_g \sum_i \delta_{gi} e^{\gamma_{gi} x_{gi,land}} - \sum_g \sum_i \sum_{j,j \neq land} (\omega_{igj} x_{gij}) \quad (15.6)$$

$$\sum_i X_{gij} \leq b_{gj} \quad \forall g,j \quad (15.7)$$

Constraint set in equation 15.7 is as in 15.3 above. In equation 15.6, the parameter *yred* is a scaling factor to accommodate different modeling policies such as yield changes due to salinity or climate change. In this model formulation water is assumed to be interchangeable among crops within a region.

Changes resulting from different water management policies, physical conditions and market-driven exogenous events can be simulated by changing parameters, and changes in production can be evaluated along both the extensive and the intensive margins.

In this study we used the most recent California Climate Assessment with CALVIN (Medellín-Azuara et al., 2008a) and SWAP (Howitt et al., 2009c). CALVIN provides economically driven water deliveries under historical and warm-dry forms of climate change by year 2050 to SWAP in a second round of modeling, as illustrated in Figure 15.2 (see p. 256).

CLIMATE CHANGE AND AGRICULTURE IN CALIFORNIA

Virtually all agriculture in California is irrigated. Every year about 3.65 million hectares are irrigated statewide using nearly 35 hm³ of water and yielding more than \$20 billion (2008) in revenues. There is a long list of agricultural commodities grown in California, including field, orchard, vine, truck and fodder crops.

The SWAP model in the present study includes 21 regions in the Central Valley known as CVPM regions (USBR, 1997), plus agricultural regions in Coachella, Imperial, Palo Verde, Ventura and San Diego. Coverage for five out of ten hydrological regions is shown in Figure 15.3 (see p. 257). The Sacramento River hydrological region covers CVPM regions 1 through 7 with portions of 8 and 9. The San Joaquin River Basin includes portions of regions 8 and 9 plus CVPM regions 10 to 13. The Tulare Basin covers CVPM regions 14 to 21. Data sets for crop budgets in SWAP are from

UC Cooperative Extensions. Land and water use information was obtained from the California Department of Water Resources (DWR).

Base Case

In the base case, SWAP includes 3.36 million hectares of irrigated agriculture and 31.9 million m³ per year for year 2005 of water for irrigation. Agricultural commodities in California are collapsed into 12 SWAP crop groups: alfalfa, citrus, corn, cotton, field crops, grains, grapes, orchards, pasture, sugar beet, tomato and truck crops. More recent versions of SWAP further disaggregate these crop groups into 20 groups.

Land Use, Technology and Climate Change for Year 2050

We employ estimates of urban footprint growth to 2050 from Landis and Reilly (2002), which suggest an overall 8.5 per cent reduction in agricultural land use from 2005 to 2050. Sanstad et al. (2008) provide estimates of the population footprint for the century, and their results for 2005 and 2050 are illustrated in Figure 15.4 (see p. 257).

Agricultural crop yields are assumed to increase over time due to technological improvements up to a certain physical photosynthetic limit. A historical 1.42 per cent annual rate of yield improvement was assumed to continue at the same rate as estimated by Brunke et al. (2004) until 2020. After 2020 this improvement is assumed to have reached a plateau due to limits from photosynthesis. Future technology is unlikely to continue to improve yields at the same rate indefinitely over time. This results in a log-linear growth rate of 0.25 for the period 2020–25, and an average increase in crop yields of 29 per cent among all SWAP crop groups by year 2050. A breakdown by crop group is presented in Howitt et al. (2009c).

A significant challenge in establishing 2050 year conditions for agricultural production is the estimation of realized crop prices. Therefore some simplifying assumptions and an endogenous crop price model were employed. It was assumed that California was a price-taker for grain, rice and corn crop groups. However, crop demand for the rest of the crops in California was assumed to increase with population and income, keeping a constant proportion of California production sold as out-of-state exports. Howitt et al. (2009c) provide additional details on demand shifts by crop group. In general, most crop prices are expected to increase by year 2015 in real terms, with a drop following. Combining these effects, rice, corn and grain might experience price drops of 1.45, 0.67 and 1.58, respectively, with resulting demand shifts of –1.4 per cent for rice, –17 per cent for corn and –19.9 per cent for grain. For crops in which California has market power, population and income projections were employed to estimate 2050 demand shifts. A US population increase of 43 per cent and ratio of real income of 2.5 with respect to 2005 were used as inputs to shift crop demands following Muth (1964). Shifts in the demand intercept range from 3.44 for field crops to 45 for truck crops. Details on the endogenous model formulations and demand shift estimations are presented Howitt et al. (2009c).

Climate-related crop yield changes are expected in California and elsewhere. These expected changes are largely the result of changes in precipitation and temperature under different climate scenarios. A handful of studies have been conducted taking these environmental conditions into account for California (Adams et al., 2003; Bloom, 2006;

Table 15.1 Expected climate-related yield changes in a climate change scenario

Crop groups	Sacramento	San Joaquin
Alfalfa	4.9	7.5
Citrus	1.77	-18.4
Corn	-2.7	-2.5
Cotton	0.0	-5.5
Field	-1.9	-3.7
Grain	-4.8	-1.4
Orchards	-9.0	-9.0
Pasture	5.0	5.0
Grape	-6.0	-6.0
Rice	0.8	-2.8

Source: Adapted from Howitt et al. (2009c).

Lee et al., 2009; Lobell et al., 2007). However, many of these studies are crop-, climate-scenario and region specific without a comprehensive assessment of all crop groups and regions in California. Thus we divided the state in two larger regions: the Sacramento and the San Joaquin River basins. Furthermore, we used a warm-dry climate scenario since most crop groups have been found to be more sensitive to water stress than to temperature changes. Among the IPCC scenarios we used GFDL CM2.1 A2. This warm-dry scenario yields a statewide-average of 4.5 °C temperature rise and an 18 per cent reduction in precipitation by the end of the century (Cayan et al., 2008). Table 15.1 presents a summary of yield changes by crop group. Crops show mixed effects of climate change by region. For example, citrus is represented by Valencia orange 2060 projections from Adams et al. (2003). The source of this regional effect could be explained in part by the use of a warm climate scenario with a 3.24 °C increase in temperature but no reductions in precipitation. However, similar studies (Lobell et al., 2006) show a statewide 90 per cent confidence band ranging from zero to nearly negative 20 per cent by mid-century. In earlier studies by Rosenzweig et al. (1996), the spatial variability of yield changes for citrus under climate change had been confirmed, unveiling once again the complexities in crop and environment interactions.

Warm-dry climate change also affects water deliveries to agricultural locations as water availability is reduced. For California under the GFDL climate scenario, a reduction in precipitation of 27 per cent, a reduction in inflows of 28 per cent and an increase of 15 per cent in reservoir evaporation are expected (Medellín-Azuara et al., 2008a). In the Central Valley, groundwater inflows can be reduced by nearly 10 per cent under this climate scenario. The resulting reduced availability of water for agriculture is summarized in Table 15.2. SWAP takes into account water availability with and without climate change to estimate economically optimal cropping patterns under climate change.

SWAP Model Policy Runs

To estimate the effect of climate change in crop production in California by 2050, we used the CALVIN and the SWAP model as shown in Figure 15.2. The three scenarios

Table 15.2 Expected percentage reduction in water availability under the warm–dry climate scenario versus the historical climate scenario under using CALVIN hydro-economic optimization

Region	Agriculture	Urban	Total
Sacramento	24.3	0.1	19.1
San Joaquin	22.5	0.0	17.6
Tulare	15.9	0.0	13.5
Southern California	25.9	1.12	8.9
Total	21.0	0.7	14.0

Source: Adapted from Medellín-Azuara et al. (2008a).

evaluated in SWAP to disentangle the effects of changes over time from 2005 to 2050 from effects that can be attributed to climate change are as follows: (1) 2005 base case with historical climate; (2) 2050 historical climate; and (3) 2050 with warm–dry climate. Base case includes 2005 land use using current farm budgets, whereas the 2050 scenarios account for technological change, urban footprint and climate-related yield changes. Results for these three scenarios are discussed in the next section.

RESULTS AND WATER MANAGEMENT INSIGHTS FOR AGRICULTURAL PRODUCTION UNDER CLIMATE CHANGE

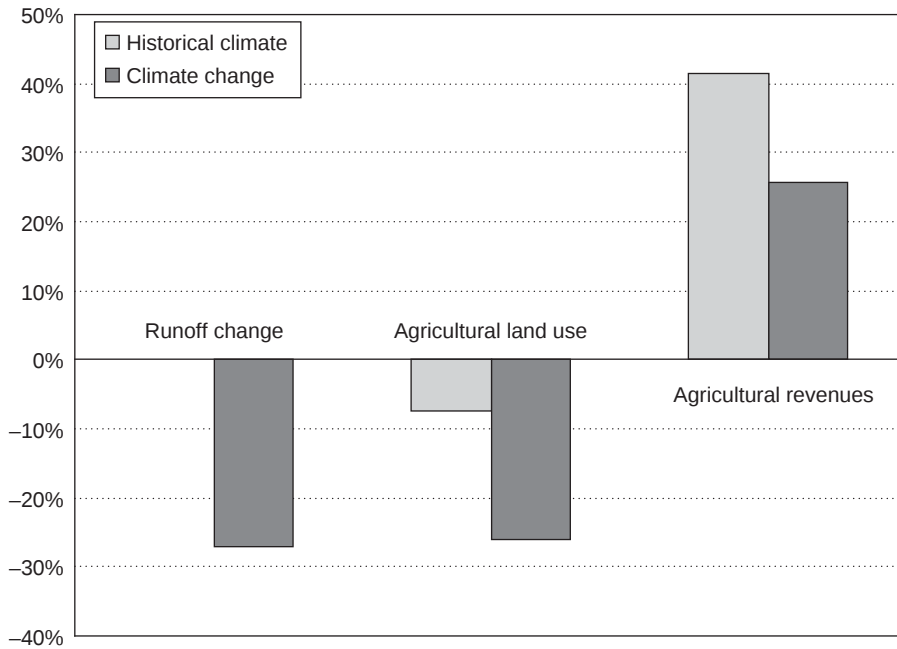
SWAP provides agricultural production results at the extensive and intensive margins. In this section we present statewide results from Medellín-Azuara et al. (in press) from the three policy scenarios. In some cases, we have grouped SWAP coverage into four larger regions: Sacramento (CVPM regions 1–9), San Joaquin (CVPM regions 10–13), Tulare (CVPM regions 14–21) and Southern California (Coachella, Imperial, Palo Verde, San Diego and Ventura).

For the agricultural areas covered by SWAP, total land, water and agricultural revenues are presented in Table 15.3. From the base case with respect to year 2005, a reduction in agricultural land use of 7.3 per cent is expected under historical climate due to changes in the footprint. Under warm–dry climate change, limits on water supplies would further reduce land use by 18.7 per cent with respect to 2005, giving a total reduction of 26 per cent. Water use behaves similarly. Total applied water under the base case scenario is 32.4 Mm³/yr, but under the historical climate scenario it drops to 30.1 Mm³/yr by year 2050, a reduction of 7 per cent. Under climate change, however, a reduction of 26.3 per cent is expected. Adaptation of agricultural production to climate drives cropping patterns toward more profitable and less water-intensive crops, reducing total water use in agriculture more than total land use. This is shown as an increase in total agricultural revenues for the areas covered by SWAP. In the base case about \$20 billion (2008) in revenues concentrated in the Central Valley (\$9 billion in the Tulare Basin) are increased to \$28.4 billion under historical climate. Climate change by year 2050 is likely to reduce agricultural revenues with respect to historical climate. However, these revenues are not reduced with respect to the base

Table 15.3 Statewide agricultural land, water and revenues for the three analyzed scenarios

Scenario	Land use (1000 ha)	Water use (Mm ³ /yr)	Revenues (\$2008 billion)
Base 2005	3 375	26 295	20.1
Historical 2050	7 727	24 433	28.4
Climate change 2050	6 170	19 368	25.2

Source: Adapted from Medellín-Azuara et al. (in press).



Source: Adapted from Medellín-Azuara et al. (in review)

Figure 15.5 Change in runoff, agricultural land use and agricultural revenues with respect to the 2005 base case

case, as more profitable and less water-intensive crops are likely to make up future crop mix.

This outcome is also illustrated in Figure 15.5, which compares runoff reductions, agricultural land use and revenues. Water deliveries closely follow land-use patterns. In isolation, climate change will have detrimental effects on agricultural production and revenues. However, the revenue losses are partially compensated by higher crop prices, technology and adaptation to less water-intensive crops. To reinforce this finding, the maps in Figure 15.6 (see p. 258) show agricultural land use, water use and revenues for the two 2050 historical climate and climate change scenarios.

Changes in statewide cropping patterns between historical and climate change

Table 15.4 SWAP crop group cultivated area by year 2050 under historical and climate change scenarios

Crop name	Historical	Climate change	% change land use	% change in crop share
Alfalfa	828 394 (335 239)	725 377 (293 550)	-12.4	9.66
Citrus	372 440 (150 721)	366 353 (148 258)	-1.6	23.18
Corn	511 374 (206 946)	405 942 (164 279)	-20.6	-0.59
Cotton	632 242 (255 859)	509 732 (206 281)	-19.4	0.96
Field crops	1 346 916 (545 078)	701 381 (283 839)	-47.9	-34.79
Grains	489 517 (198 101)	332 113 (134 401)	-32.2	-15.04
Grapes	633 381 (256 320)	625 491 (253 127)	-1.2	23.67
Orchards	747 062 (302 325)	737 691 (298 533)	-1.3	23.66
Pasture	251 456 (101 761)	9 912 (4 011)	-96.1	-95.06
Rice	555 348 (224 741)	427 687 (173 079)	-23	-3.56
Tomato	318 313 (128 817)	316 685 (128 158)	-0.5	24.59
Truck crops	1 040 768 (421 184)	1 012 028 (409 553)	-2.8	21.77
Total	7 727 211 (3 127 091)	6 170 392 (2 497 069)	-20.1	N/A

Source: Adapted from Medellín-Azuara et al. (in press).

scenarios by year 2050 are shown in Figure 15.7 (see p. 259). Pasture is reduced substantially in regions that cannot afford that land use if a 27 per cent reduction in rim inflows occurs under climate change. Corn and cotton follow a similar response. One limitation of the representation of SWAP of corn and pasture in Medellín-Azuara et al. (in press) is that silage constraints were not included in the model.

To better show the difference in cropping patterns between historical and climate change scenarios by year 2050, Table 15.4, column 5 shows the changes in land share among crops. Lower-value and water-intensive crops such as pasture will have their land share reduced to almost zero. In addition, even when crops such as alfalfa, citrus and grapes have statewide reductions in total land use, these crops increase their land share relative to other crops under climate change.

SWAP crop group prices are shown in Table 15.5. Most SWAP crop groups have price increases by year 2050. Climate change puts additional pressure on land and water use, further driving up prices.

Table 15.5 SWAP crop groups price changes among the three scenarios

	Base case 2005 price, \$/ton	Historical 2050 price, \$/ton	Climate change 2050 price \$/ton	% change 2050 historical vs climate change
Alfalfa	117	111	116	3.90
Citrus	436	410	460	12.26
Corn	102	119	119	0.02
Cotton	1701	1739	1759	1.16
Field crops	295	305	305	0.06
Grains	298	238	238	0.04
Grapes	847	962	980	1.87
Orchards	1445	1257	1358	8.05
Pasture	76	80	80	0.07
Rice	290	273	277	1.55
Tomato	50	61	61	-0.38
Truck crops	277	410	421	2.72

Note: Figures in 2008 dollars.

Source: Adapted from Medellín-Azuara et al. (in press).

The results above show that climate change will adversely affect water availability and water use in agriculture by year 2050. Reductions in most crop yields are also likely under most climate change scenarios. However, improvements in technology and rising crop prices partially offset climate change losses.

Some model limitations are worth discussing. From the hydro-economic modeling with CALVIN, it is assumed that water can be traded freely among users. In reality, some institutional constraints and high transaction costs may prevent some CALVIN economically optimal water allocations from happening. For example, modeling with SWAP in 2050, crop demand projections are an endeavor characterized by many changing variables. These include exports, competition from foreign production, growth in export demand and changing preferences. On the other hand, livestock production in California significantly influences cropping patterns of alfalfa, pasture and corn to the extent that the agronomic estimates used to calibrate the SWAP and the CALVIN models are uncertain; this uncertainty will be reflected in the integrated results of these models.

LIMITATIONS

As with any model, there is always room for improvement in SWAP. Limitations in this study arise from different sources, including model architecture, data availability and quality and inputs from other models. Model architecture and data limitations have been discussed elsewhere (Howitt et al., 2009c; Medellín-Azuara et al., 2010). Land and water use data are getting better over time with the use of remote sensing and GIS, and so is cost information. Cost information becomes important when investigating changes

in net revenues, but has less of an impact for gross revenues, which are more precisely measured in country agricultural commissioner's report (http://www.nass.usda.gov/Statistics_by_State/California/Publications/Ag_Comm/Detail/index.asp).

An interesting limitation is use of just two climate scenarios: historical and warm-dry climate change. Water availability reductions from CALVIN are approximately in line with climate change estimated reduction in surface inflows. Most of the studies on climate change and crop yields suggest that even though models are susceptible to high temperatures, water availability is more vulnerable to reductions in precipitation than increases in temperature (Connell, 2009). Thus negative economic impacts on agriculture under climate change are presumably higher under a warm-dry climate change scenario than under a warm-only scenario with historical or higher-than-average precipitation. Technological change and higher crop prices can partially compensate for some yield loss due to temperature alone. Yet water availability has potentially the highest economic impact for agriculture under climate change. In this sense, comparing climate scenarios that include both ends of water availability seems a reasonable approach to account for economic impact of climate-related yield changes in agriculture.

CONCLUSIONS

In this chapter we assessed the effects of climate change in California agriculture by year 2050 using the California Agricultural Production Model (SWAP) in combination with CALVIN, a statewide hydro-economic model for water resources in California. In estimating production conditions to year 2050, urban footprint, technological improvements and likely crop demands and price trends were taken into account. In addition, estimates from associated agronomic studies were used in the calibration of the economic production model. The warm-dry form of climate change, the GFDL CM2.1 A2, was used to evaluate changes in water deliveries to agriculture from CALVIN, and changes in agricultural yields in SWAP.

Results show that water shortages for crops are one of the major outcomes of climate change in California. Climate-induced agricultural land loss significantly exceeds the area needed to accommodate the 2050 urban footprint in agricultural areas. This unused cropland with minimal water supplies will pose a challenge for conversion to environmental habitat. The increasing value of water, which accompanies its increased scarcity, induces changes in crops and technology that are reflected in the results of the production model.

Increases in yield due to technological improvements and in prices of some crops in California are expected by year 2050. Under climate change, relative to historical climate, we model changes in yields (mostly negative) and changes in water availability. Prices are shown to increase (moderately, and some actually decrease) in response to climate change. There are changes in production of each crop and changes in total land use as a result. Revenues across all regions decline under climate change compared with a continuation of historical climate. However, total revenue increases with respect to the 2005 base case. Adaptation by reductions in land area and water use can be compensated by changes in cropping pattern, water use, market prices and crop productivity. While the effect of climate change is manifest through yield changes, after economic adaptation

the results on irrigated crop production are predominantly shown in economic terms and changes in aggregate land and water use.

ACKNOWLEDGMENTS

The authors are grateful for the data and comments provided by the California Department of Water Resources staff, including Ray Hoagland, Farhad Farnam and Thomas Hawkins. Research support from Duncan MacEwan in modeling and Chenguang Li in assembling our data sets was extremely helpful. This study was partially funded by the California Energy Commission's Public Interest Energy Research (PIER).

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16 Reducing the impact of global climate change on agriculture – the use of endogenous irrigation and protected agriculture technology

Aliza Fleischer and Pradeep Kurukulasuriya

INTRODUCTION

Climate change is threatening agricultural production in various world regions and the livelihoods of millions of poor rural people are at risk, especially in the low latitudes (IPCC 2007; Parry et al., 2004). Large potential damages have been predicted by many agronomic studies (Rosenzweig and Parry, 1994; Parry et al., 2004; IPCC, 2007). However, these studies assume that farmers will not adapt to the new climate conditions. In contrast, studies that account for adaptation suggest smaller damages (Mendelsohn et al., 1994; Mendelsohn and Dinar 2003; Kurukulasuriya et al., 2006; Fleischer et al., 2008; Seo and Mendelsohn, 2007; Wang et al., 2009). There is a growing body of farm adaptation studies that identify what adaptation strategies farmers might make to mitigate potential damage. Specifically, farmers might invest in irrigation (Mendelsohn and Dinar, 2003; Kurukulasuriya et al., 2006; Mendelsohn and Seo, 2007), they might switch crop species (Kurukulasuriya and Mendelsohn, 2008a; Seo and Mendelsohn, 2008b) or they might switch livestock species (Seo and Mendelsohn 2007).

Irrigation is the adaptation strategy that has received most attention in the literature. Several studies estimate separate response functions for rainfed and irrigated farms. These studies reveal that farmers who irrigate are less sensitive to climate changes (Schlenker et al., 2005; Kurukulasuriya and Mendelsohn, 2008a; Seo and Mendelsohn, 2008a). This type of analysis captures the effect of irrigation but it assumes that irrigation is exogenous. We claim that irrigation and the use of other technologies are likely to be sensitive to climate conditions and will change as climate changes. The fact that irrigation is not exogenous but a choice farmers make has already been established in the literature (see Caswell and Zilberman, 1986; Dinar and Yaron, 1990; Negri and Brooks, 1990; Dinar and Zilberman, 1991; Dinar et al., 1992). Our unique contribution is showing that the decision of adopting a technology is also a function of climate conditions.

We show the effect of climatic conditions on technological adaptation in two world regions, Africa and Israel. Studying the impacts of climate change in Africa is very important because low-latitude countries are more vulnerable than mid- to high-latitude countries. They are hotter, have a larger fraction of their economy in agriculture and have less wealth and technology for adaptation. The Israeli case is presented here in order to show that technological adoption can serve as a strategy to mitigate the harmful effects of climate change on farm earnings.

This chapter proceeds as follows: in the next section, we present the theoretical models that underpin the analysis presented in this chapter. We examine the impact that the

selection of a specific adaptation technology (irrigation) has on expected farm revenues. The analytical framework is tested and applied using farm data from Africa where we build an endogenous irrigation model and test this model using a sample of over 10000 plots across 11 African countries. Results are presented including simulations of expected welfare change based on a number of IPCC-endorsed climate change scenarios. The chapter then presents analysis from Israel and an alternative theoretical model is applied in a context where technology and capital are used extensively to overcome climate-induced pressures. We examine the adoption of types of irrigation technology in the context of different land-use cover and test whether these decisions are sensitive to climate. We conclude with policy recommendations.

THEORETICAL MODEL

The following model is a ‘Structural Ricardian’ model where the government and/or a farmer chooses to adopt an endogenous technology (e.g. an irrigation technology) based on what would maximize the value of all resources. We estimate a two-stage model where the first stage is the choice of whether to adopt the technology or not and the second stage is the conditional income that is earned by different types of farmers. The latter could include those who farm under rainfed conditions or those who farm under irrigated conditions. The underlying theoretical structure of this model assumes that decision makers maximize net revenues:

$$\text{Max } \Pi = P_i Q^*(X, E) - WX \quad (16.1a)$$

where Π is net revenue, P_i is output prices, Q^* is output, X are chosen inputs, E is environmental factors such as climate and soils and W is the price of inputs. The model assumes that the amount of cropland is fixed.¹ Net revenue is defined broadly to include not only sold goods but also goods consumed by the household.

We develop a sample selection model (Heckman, 1979). However, there is an important difference between this case and the labor selection model. In the labor example people who did not work have no observed income. In this model, farmers who choose not to adopt a specific technology still have observed income from farming under non-irrigated conditions (e.g. rainfed farming).

We assume that the choice of adopting a specific technology is made if it is deemed to be more profitable than farming without that technology. Clearly the cost of the technology lies largely in expensive capital. The government and the farmer must weigh whether the present value of the additional annual returns from adopting the technology is worth the cost. The higher the additional net revenue each year, the more attractive the adoption of that technology becomes. In the first stage, we estimate a dichotomous choice model of irrigation, Y , where $Y = 1$ is irrigation (1) and $Y = 0$ is rainfed farming:

$$Y_i = \beta^1 X + \mu_i \quad (16.2a)$$

We identify the choice equation with various factors that are determined to affect choice, including at least one identification variable that is determined to affect choice

but not the second stage conditional equation. In the second stage we estimate a conditional profit function for each type of farming based on the available exogenous variables, Z :

$$\Pi_i = \gamma^I Z^I + \mu_2 \text{ if } Y = 1 \quad (16.3a)$$

$$\Pi_d = \gamma^D Z^D + \mu_3 \text{ if } Y = 0 \quad (16.4a)$$

where Y_1 is a latent variable explaining the choice of technology that is adopted, Π_i is the net profit of farms that have chosen to adopt the technology, and Π_d is the net profit of farms that have chosen to not adopt the technology, X is a k -vector of regressors, Z^I is an m -vector of regressors for irrigation, Z^D is an n -vector of regressors for rainfed, and the error terms μ_1 and μ_2 and μ_1 and μ_3 are jointly normally distributed, independently of X and Z , with zero expectations.

$$\mu_1 \sim N(0, 1)$$

$$\mu_2 \sim N(0, \varphi_2)$$

$$\mu_3 \sim N(0, \varphi_3)$$

$$\text{corr}(\mu_1, \mu_2) = \rho_2$$

$$\text{corr}(\mu_1, \mu_3) = \rho_3$$

It should be noted that the use of a specific technology that is adopted is observed only if it is more profitable than non-adoption. Thus the observed dependent variable Y is:

$$Y = 1 \text{ if } \Pi_i > \Pi_d$$

$$Y = 0 \text{ if } \Pi_d > \Pi_i$$

When $\rho_2 = 0$, an ordinary least squares (OLS) regression could provide unbiased estimates of the coefficients for the conditional irrigation equation, but when $\rho_2 \neq 0$ the OLS estimates are biased. A parallel result holds for ρ_3 and the regression coefficients in the equation where the technology is not adopted. We consequently employ the inverse Mills ratio from the selection model in both the technology adopted and technology not-adopted conditional regressions in order to control for selection (Heckman, 1979). We expect the signs on the coefficient of the inverse Mills ratio to be the opposite in each regression.

An alternative approach presented in this chapter applies when the technology for adapting to climate change is pervasive but is applied under different types of protected agriculture techniques (e.g. greenhouses, nets, plastic tunnels). The analytical framework in such cases is presented as follows: the profit function for a farm growing J crops as:

$$\pi = \sum_{j=1}^J [p_j Q_j(z, m, x_j, I_j) - w x_j - p_I I_j], j = 1, 2, \dots, J \text{ crops} \quad (16.1b)$$

where p_j are crop prices, Q_j production functions, z is a vector of climate variables, m is a vector of exogenous farm characteristics including water quota, x_j is a vector of crop's j inputs and I_j is the amount of technology (e.g. irrigation water) used by the farmer for crop j , w is a vector price of x and p_I is the price of water.

A profit-maximizing farmer will choose x_j satisfying the following condition for all n endogenous inputs:

$$p_j \frac{\partial Q_j}{\partial x_j} = w \quad j = 1, \dots, J \quad (16.2b)$$

These conditions define the optimal choice of x_j as a function of z, m, I denoted $x_j(z, m, I)$ under the assumption that p_j and w are uniform across the country. Similarly, by maximizing (16.1) with respect to I_j , the first-order conditions for water for crop j are:

$$p_j \frac{\partial Q_j(z, m, I_j)}{\partial I_j} = p_I \quad \forall j \quad (16.3b)$$

Under these assumptions the farm function demand for a technology can be expressed as a function of M climate conditions and L farm characteristics:

$$I = \alpha'_0 + \sum_{i=1}^M \alpha'_i \ln(z_i) + \sum_{l=1}^L \gamma'_l m_l \quad i = 1, 2, \dots, M \quad l = 1, 2, \dots, L \quad (16.4b)$$

where $I = \sum_{j=1}^J I_j$, α' and γ' are coefficients of the climate and exogenous variables, respectively. Although clearly demand functions are normally expressed in terms of price, the prices farmers face in this cross-section are largely the same. Consequently, we do not observe any price variation and can merely measure factors that shift the demand function.

The demand function for protected agriculture techniques is derived similarly from the profit function and can be expressed as follows:

$$C = \alpha^C_0 + \sum_{i=1}^M \alpha^C_i \ln(z_i) + \sum_{l=1}^L \gamma^C_l m_l \quad i = 1, 2, \dots, M \quad l = 1, 2, \dots, L \quad (16.5b)$$

Where $C = \sum_{j=1}^J C_j$, α^C and γ^C are coefficients of the climate and exogenous variables respectively. Again, we do not expect any variation in the price of inputs for the protected agriculture technology within the cross-section.

CASE A: AFRICA

With over 40 per cent of the African continent's population living on less than US\$1/day and 70 per cent of these poor located in rural areas and largely dependent on agriculture for their livelihoods, adverse shifts in climate are expected to cause declines

in human welfare. Climate change is expected to exacerbate existing economic, political and humanitarian stress. By 2020, 75–250 million people across Africa could face water shortages (UNDP, 2009). Previous research has demonstrated that under conditions of declining rainfall and rising temperature, net revenues from rainfed agriculture could fall by more than 60 per cent in some African countries (Kurukulasuriya and Mendelsohn, 2008a). While a number of crops such as maize, a mainstay of southern African diets, are already experiencing drought stress on an annual basis, climate change will most likely exacerbate such type of pressures. At the same time a number of crops are well suited for hot and dry climates or cooler and wet climates. Kurukulasuriya and Mendelsohn (2008b) demonstrated how farmers in cooler regions of Africa choose maize–beans and sorghum, whereas those in hot regions choose cowpea and millet. Other combinations such as millet and sorghum are chosen in dry regions, while maize–beans, cowpea–sorghum and maize–groundnut are the choice in wet regions. Their study found that farmers often choose crop combinations to survive the harsh conditions in Africa such as maize–beans, cowpea–sorghum and millet–groundnut. These combinations provide the farmer with more flexibility across climates than growing a single crop on its own.

It is expected that farmers will alter future crop choices as the climate changes, provided there are no barriers to the adoption of appropriate crops. One of the barriers that is often intuitively assumed to support resilience to climate change, assuming there is sufficient flow, is the use of irrigation technology. This chapter tests this hypothesis in two different contexts – Africa, where rainfed agriculture dominates with some limited use of irrigation, and Israel, where irrigation dominates but is applied in different types of protected agriculture techniques.

Data

The empirical analysis is based on a household survey of farms conducted in 11 countries across Africa: Burkina Faso, Cameroon, Egypt, Ethiopia, Kenya, Ghana, Niger, Senegal, South Africa, Zambia and Zimbabwe.² The sample was chosen to select farms across a wide range of climates within each country. The sample across the 11 countries has approximately the same mean characteristics as farms in the continent have.

As many African countries do not have formal land markets, collecting land values is difficult. Instead, we rely on measurements of net revenue per hectare. Net revenues are appropriate measurements of the annual net productivity of the land. However, compared to land values net revenues are a more volatile measure since they reflect factors that change year by year. Net revenue is defined as gross revenue minus the cost of transport, packaging and marketing, storage, post-harvest losses, hired labor (valued at the median market wage rate), light farm tools (such as files, axes, machetes etc.), rental on heavy machinery (tractors, ploughs, threshers and others), fertilizer and pesticide. Median district prices from the survey were used in estimating the values of both input and crop prices. Household labor costs are not included as a cost in net revenues because it was not clear what value to assign to wages. We controlled for household labor by using household size as a proxy.

In each country, districts were chosen in order to sample farms across a wide range of agro-climatic conditions. In each chosen district a random but clustered sample of farms was selected. After data cleaning, which included removing farms that did not grow

Table 16.1 Sample of farms – Africa analysis

Country	No. of plots	Irrigated plots	Rainfed plots
Burkina Faso	1141	59	1082
Cameroon	1013	145	868
Egypt	1030	1030	0
Ethiopia	932	67	865
Ghana	1210	49	1161
Kenya	862	95	767
Niger	1133	52	1081
Senegal	1362	34	1328
South Africa	283	83	200
Zambia	1009	13	996
Zimbabwe	958	123	835
Total	10933	1750	9183

crops and surveys with field errors and missing information, the final number of usable surveys (farms) was 8463. We conducted the analysis at the plot level of each farm. There are 10915 plots in the data set. Each farm provided plot-specific data on whether or not irrigation was used, crop production (including crop type, amount harvested, quantity sold, quantity consumed and amount of sales receipt) and crop costs (fertilizer, pesticide and seed data). Using these data, prices per crop and yields per hectare of farmland and cropland were estimated, as well as plot specific crop revenues and farm-level gross and net revenues. The estimated prices and yields were validated based on official records of district- and national level prices and yields per hectare. Net revenue estimates are at the farm level because the input data, including labor (both hired and household) and machinery, were available only at that unit of measurement. It was not possible to allocate most inputs to specific plots as much of it was applied to several plots at a time. The data set we used contains 1750 irrigated plots and 9183 rainfed plots. The distribution of surveys – irrigated and rainfed plots by country – is shown in Table 16.1. The farm plots reflect a representative sample of African agro-ecological zones.

Because net revenue data are available for only one year, the survey asked farmers whether the weather was average or atypical in the year of the survey. The large majority of the farmers reported that the weather was typical. Because the size of the weather aberrations is small in this particular survey, it is not expected that they will bias the results. The fact that there is only one year of revenue data for each site, however, does make these data unsuitable for studying climate variance.

This study relies on climatic normals (mean long-term weather) of both precipitation and temperature for each district. The monthly temperature data comes from US Department of Defense satellite measurements between 1988 and 2003 (Basist et al., 2001). This set of polar orbiting satellites takes measurements at every location on earth at 6 am and 6 pm every day. The satellites are equipped with sensors that measure surface temperature by detecting microwaves that pass through clouds (Weng and Grody, 1998). Satellites, however, cannot measure precipitation. The monthly precipitation data come from the Africa Rainfall and Temperature Evaluation System (ARTES) (World Bank,

2003). This data set, created by the National Oceanic and Atmospheric Association's Climate Prediction Center, is interpolated from ground station measurements of precipitation over the period 1948–2001. This combination of using temperature measurements from satellites and precipitation data from ground stations provides the best available climate measures for agricultural analysis (Mendelsohn et al., 2006a). The average temperatures and precipitation for each country in the sample are shown in Appendix A. Note that there is a wide range of climates across the 11 countries in the sample.

It is not possible to use every month of climate in a Ricardian regression because of the high correlation between one month and the next. Consequently, we clustered the monthly data into three-month seasons. We explored several alternatives but finally selected November, December and January as 'winter', February through April as 'spring', May through July as 'summer' and August through October as 'fall'. These seasonal definitions provide the best fit with the data. We adjusted for the fact that seasons in the Southern and Northern hemispheres occur at exactly the opposite months of the year. Note that although Egyptian and South African climates resemble mid-latitude seasonal climates, the distribution of temperatures in countries near the equator is quite different with very warm springs and summers. Rainfall depended on monsoons, which tended to come in fall and winter. Soil data from FAO (2003) are included in this analysis. The FAO data provide information about the major soil, soil texture and slope in each location. Data concerning the hydrology are based on the predicted output from a hydrological model for Africa developed for this study (IWMI and University of Colorado, 2003). The model calculated the water flow through each district in the surveyed countries in each season. Flow is an especially important variable because it describes the amount of water coming into a district from higher elevations. Kurukulasuriya and Mendelsohn (2008b) found that lower flow is associated with farmers choosing maize–beans, cowpea–sorghum, maize–groundnut, maize–millet, millet–groundnut and fruits–vegetables. Lower flow probably implies that farmers cannot irrigate.

Data on elevation at the centroid of each district are from the US Geological Survey (USGS, 2004). The USGS data are derived from a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 km).

During pre-testing of the survey instrument³ it was clear that some farmers cultivated at least two plots of land. Subsequently, the survey data collected crop data, including production quantities, amount sold and sale receipts from crops for the largest single plot of cultivated land (referred to hereafter as the main plot) and all others (referred to as the secondary plot). The following analysis is based on these plot data.

We tested whether clustering affected the significance of the reported results. Clustering is not expected to bias the coefficients but it is expected to reduce the significance of the coefficients. We find that a comparison of the marginal climate effects when clustering is controlled with the analysis presented in this chapter suggests that the results remain significant and robust.⁴ The predictive ability of the model is not compromised by clustering.

Results

With the African plots, Table 16.2 presents the first stage of the analysis, a probit model of whether a plot is irrigated or not. There are 10915 plots with complete information

Table 16.2 *Probit model of whether to irrigate – Africa analysis*

Variable	Coefficients	Variable	Coefficients
Temp. – winter	0.45* (3.00)	Chromic Cambisols – medium, steep	–1.54* (–2.51)
Temp. – winter sq.	–0.003 (–0.67)	Lithsols – coarse, medium, Fine, steep	–5.20* (–1.99)
Temp. – spring	–0.95** (–6.03)	Ferric Luvisols – coarse, undulating	1.09** (8.69)
Temp. – spring sq.	0.01* (2.48)	Gleyic Luvisols	0.84* (2.60)
Temp. – summer	1.25** (9.42)	Gleyic Luvisols – medium, undulating	0.78* (2.96)
Temp. – summer sq.	–0.02** (–9.43)	Chromic Luvisols – Medium, undulating, hilly	0.53 (1.00)
Temp. – fall	–0.71** (–4.25)	Luvic Arenosols – coarse, undulating	–4.70** (–3.76)
Temp. – fall sq.	0.02** (5.54)	Lithosols and Eutric Gleysols – hilly	7.25* (2.54)
Precip. – winter	–0.01 (–1.89)	Calcic Yermosols – coarse, medium, undulating, hilly	2.74** (5.28)
Precip. – winter sq.	0.00** (5.06)	Eutric Gleysols – Coarse, Undulating	–2.71 (–1.51)
Precip. – spring	–0.01* (–2.20)	Chromic Vertisols – fine, undulating	0.6 (1.06)
Precip. – spring sq.	0.0000025 (0.10)	Chromic Luvisols – medium, Fine, undulating	–0.27 (–0.61)
Precip. – summer	0.02** (6.37)	Chromic Luvisols – medium, steep	–0.52 (–0.31)
Precip. – summer sq.	–0.000067** (–5.48)	Dystric Nitosols	–1.02* (–2.06)
Precip. – fall	–0.01** (–3.25)	Lithosolus – hilly, steep	–0.06 (–0.09)
Precip. – fall sq.	0.000036** (4.00)	Orthic Luvisols – medium, hilly	–1.5 (–1.21)
Plot area (ha)	0.000067 (0.59)	Flow – winter	–1.67 (–1.73)
Log(elevation)	0.26** (8.13)	Flow – winter sq.	–0.8 (–1.17)
Log(household size)	0.09* (2.03)	Flow – spring	–0.05 (–0.06)
Household with electricity (1/0)	0.23** (4.33)	Flow – spring sq.	2.12* (3.20)
Gleyic Luvisols – fine, undulating	–7.34* (–1.98)	Flow – summer	–1.24** (–4.83)
Eutric Gleysols	–2.54** (–6.57)	Flow – summer sq.	0.11** (4.55)

Table 16.2 (continued)

Variable	Coefficients	Variable	Coefficients
Flow – fall	1.22** (5.58)	Constant	–4.18** (–3.73)
Flow – fall sq.	–0.08* (–3.28)	<i>N</i>	10915
		Log pseudolikelihood	–2122.1
		<i>R</i> ²	0.56

Note: Dependent variable is whether or not irrigation is utilized in a plot. * $p < 0.05$; ** $p < 0.01$. *z* statistics are in parentheses. *Soil texture*: coarse soils have less than 18% clay and more than 65% sand, medium soils have less than 35% clay and less than 65% sand, and fine soils have more than 35% clay. *Soil slope*: undulating with less than 8% slope, hilly with slopes between 8% and 30%, and steep with more than 30% slope.

for the regression. The explanatory variables in the first stage include seasonal climatic variables, farm characteristics, soils, altitude and seasonal water flow. Both linear and quadratic climate and flow variables are introduced in the probit to capture nonlinearities in climate responses. The quadratic temperature, precipitation and flow variables are significant. The reported standard errors in the chapter are based on the Huber–White estimator of variance, which is robust against many types of misspecification of the model (Heltberg and Tarp, 2002).

The seasonal district surface water flow variables and altitude identify choice. The coefficients on most of these variables are significant. The return to irrigation is much higher at high altitudes in Africa. Higher altitudes increase the chance that farmers choose irrigation. Also, once one controls for climate, altitude has little effect on conditional net revenues. Higher district water flows also make it easier to irrigate. Higher water flows in each season except winter make irrigation a more attractive (possible) alternative. Note that this is not the water available to a specific farmer but rather the exogenous water flow in a district.

Moreover, in terms of our modeling framework, water flows are not expected to affect conditional earnings because district water flows do not measure the amount of water directly available to a farmer. The availability of water is not just a farmer's decision; it is also often a choice by government officials. In this study, we use the natural surface water flows in a political district to identify the availability of water. This is an exogenous measure of water availability, not an endogenous choice. Of course, climate change could change water availability.

In the selection model we also control for soils and other farm characteristics. The soil variables reflect the proportion of a district with a particular soil type. The effects of types of soils vary depending on slope and soil texture. Soils can increase or reduce the probability of irrigation depending on whether they are hilly, undulating (positive) or steep (negative). Often, fine soils are negatively associated with irrigation and medium soils are positively associated. Electricity is positively associated with irrigation. This may reflect the role of electricity in pumping or just access to markets. Plot size is not related to irrigation choice. Larger households (more people) are more likely to irrigate, which suggests that irrigation is labor intensive on a per hectare basis. Other household variables such as education, age and experience were not significant.

Table 16.3 Marginal climate impacts – probit model (Africa analysis)

	Selection model (irrigation choice)		
	Temperature °C	Precipitation mm/mo	Flow million m ³ /mo
Winter	0.34 (0.062)	−0.002 (0.005)	−2.49 (0.83)
Spring	−0.52 (0.068)	−0.01 (0.004)	1.47 (0.85)
Summer	0.08 (0.58)	0.01 (0.002)	−0.9 (0.28)
Fall	0.15 (0.059)	−0.002 (0.002)	0.91 (0.20)
Annual	0.06 (0.016)	−0.01 (0.004)	−1.06 (0.58)

Note: Marginal effects calculated from coefficients in Table 16.2.

The climate and flow coefficients are highly significant. However, with the quadratic functional form they are difficult to interpret. Using the coefficients in Table 16.2, we present the mean marginal impact of temperature, precipitation and flow in Table 16.3. The probability of adopting irrigation increases with higher temperatures in each season except spring. The annual effect of higher temperatures increases the probability of adopting irrigation. Irrigation allows crops to withstand higher temperatures, and the combination of irrigation and higher temperatures allows for multiple seasons. The probability of adopting irrigation falls with more precipitation in every season except summer. With more rain, farmers can grow crops without irrigation, making the cost of irrigation unnecessary. The probability of adopting irrigation falls if there is a uniform annual increase in surface flows across all seasons. However, this is because flow during the winter season is very harmful, probably causing damage to irrigated systems. Flow during the spring and fall substantially increases the probability of irrigation. In general, farmers favor irrigation in warmer and drier African climates with good flow in the spring and fall.

The second-stage model of net revenue conditional on irrigation choice is shown in Table 16.4. The dependent variable is annual net income per hectare and the independent variables include climate, soils and other control variables. We present two sets of regressions. Columns (b) and (d) are estimated with OLS. Following the standard selection model (Heckman, 1979), we include the inverse Mills ratio in columns (a) and (c) to control for self-selection bias in the second-stage OLS model. In both cases there is one regression for rainfed plots and one for irrigated plots. The coefficient on the estimated Mills ratio is not significant, but it has the negative sign expected in the rainfed regression. Comparing the regression coefficients in the OLS and corrected models reveals that they are not significantly different. There is little evidence of selection bias.

Farm size is significant and negative for both irrigated and rainfed plots. Larger plots have lower net revenue per hectare. This is probably due to our omission of household labor as a cost in net revenue (a measurement bias). Household labor per hectare will tend to be greater in smaller plots. The result may also be due to higher management intensity on smaller plots (a real effect). We also include a dummy variable that denotes whether or not a farm has electricity. Electrified farms outperform farms that do not have electricity in both the irrigated and rainfed models. Electrification might directly enhance productivity and earnings, or it may simply be a proxy for farms that are closer

Table 16.4 Conditional income regressions (Africa analysis)

Variables	Irrigated model		Rainfed model	
	Corrected	OLS	Corrected	OLS
Temp. – winter	97.0 (0.60)	142.4 (1.05)	-128.2* (-2.51)	-123.4* (-2.43)
Temp. – winter sq	-1.69 (-0.44)	-2.65 (-0.74)	4.33** (3.31)	4.25* (3.25)
Temp. – spring	-93.2 (-0.47)	-165.4 (-1.07)	4.3 (0.05)	-4.7 (-0.05)
Temp. – spring sq.	-0.60 (-0.15)	0.68 (0.19)	-1.98 (-1.09)	-1.84 (-1.03)
Temp. – summer	1188.1** (3.42)	1287.9** (4.74)	214.2* (3.24)	224.7** (3.51)
Temp. – summer sq.	-18.16* (-3.02)	-20.16** (-4.48)	-2.99* (-2.36)	-3.19* (-2.60)
Temp. – fall	-1580.4** (-3.63)	-1653.8** (-4.31)	-82.6 (-1.47)	-92.4 (-1.70)
Temp. – fall sq.	29.43** (3.47)	31.28** (4.35)	1.13 (0.95)	1.37 (1.20)
Precip. – winter	12.03 (1.80)	10.47 (1.75)	-2.60* (-2.20)	-2.74* (-2.33)
Precip. – winter sq.	-0.06 (-1.44)	-0.05 (-1.42)	0.02* (2.75)	0.02* (3.01)
Precip. – spring	-10.31 (-1.61)	-9.71 (-1.53)	3.71** (3.41)	3.78** (3.50)
Precip. – spring sq.	0.09* (2.30)	0.09* (2.27)	-0.01 (-1.44)	-0.01 (-1.59)
Precip. – summer	26.25** (4.98)	27.87** (6.46)	4.09** (6.08)	4.21** (6.27)
Precip. – summer sq.	-0.10** (-4.88)	-0.10** (-5.82)	-0.02** (-5.29)	-0.02** (-5.39)
Precip. – fall	-25.35** (-5.00)	-26.85** (-6.25)	-1.21* (-2.15)	-1.28* (-2.32)
Precip. – fall sq.	0.08** (4.98)	0.09** (5.92)	0.01** (5.53)	0.01** (5.65)
Plot area (ha)	-0.15* (-2.39)	-0.14* (-2.31)	-0.29** (-4.54)	-0.29** (-4.53)
Log(household size)	41.68 (0.74)	44.28 (0.79)	22.46* (2.05)	23.25* (2.12)
With electricity (1/0)	387.4** (3.66)	412.9** (4.36)	124.1** (7.84)	125.5** (8.03)
Eutric gleysols – coarse undulating	-1554* (-2.25)	-2045** (-3.81)	-405** (-4.54)	-424** (-4.75)
Chromic vertisols – fine undulating	-1910* (-2.81)	-1858* (-2.80)	-708** (-3.51)	-711** (-3.53)
Lithosolus – hilly steep	-878* (-3.29)	-922** (-3.51)	-353** (-8.40)	-370** (-8.96)

Table 16.4 (continued)

Variables	Irrigated model		Rainfed model	
	Corrected	OLS	Corrected	OLS
Orthic luvisols – medium hilly			–1886** (–3.81)	–1907** (–3.86)
Chromic luvisols – medium fine undulating			–315** (–8.79)	–305** (–8.72)
Chromic luvisols – medium steep	–6511* (–2.94)	–6496* (–2.92)		
Dystric nitosols	7528** (5.39)	7410** (5.28)		
Inverse mills ratio	–102.2 (–0.80)		–7.8 (–1.35)	
Constant	4361.7* (2.72)	4141.1* (2.48)	–295.6 (–0.66)	–276.1 (–0.62)
<i>N</i>	1787	1787	9128	9128
<i>R</i> ²	0.25	0.25	0.16	0.16
<i>F</i> -stat	68.47	53.6	49.41	51.11

Notes: Dependent variable is net revenue per hectare. * $p < 0.05$; ** $p < 0.01$, t-statistics in parentheses. *Soil texture:* coarse soils have less than 18% clay and more than 65% sand, medium soils have less than 35% clay and less than 65% sand, and fine soils have more than 35% clay. *Soil slope:* undulating with less than 8% slope, hilly with slopes between 8% and 30%, and steep with more than 30% slope.

to markets or are more modern. Farms with larger households have higher net revenue in both samples but the coefficient is significant in only the irrigated sample.

The second-stage regressions also give important insights into the climate sensitivity of farms. The results show that rainfed and irrigated farms are both sensitive to climate but have different climatic responses. In order to interpret the climate coefficients, the mean marginal impact is presented in Table 16.5. Annual higher temperatures have no effect on irrigated farm income, as seasonal effects are offsetting. Annual precipitation does not have a significant effect on irrigated farm income either, although wetter summers are beneficial and wetter falls are harmful. Higher annual temperatures reduce the income from rainfed plots with harmful effects from warmer springs and falls but offsetting beneficial effects from warmer winters and summers. Although these seasonal results are quite different from US results (Mendelsohn et al., 1994; Mendelsohn and Dinar, 2003), one must remember that spring is often the hottest season in Africa. More annual precipitation increases income on rainfed plots. Precipitation is especially beneficial in the spring and harmful only in the winter. The standard deviations in Table 16.5 were calculated using bootstrapping. The temperature and precipitation response functions for irrigated and rainfed farms in Africa are presented in Figures 16.1 and 16.2.

Although the analysis above makes a strong attempt to adjust for some unwanted variation by introducing available control measures, there are many variables affecting farm income that cannot be measured. In particular, there may be a number of variables

Table 16.5 Marginal climate impacts – conditional income models (Africa analysis)

	Conditional income		Conditional income	
	Irrigated Farms		Rainfed Farms	
	Temperature °C	Precipitation mm/mo	Temperature °C	Precipitation mm/mo
Winter	45 (128)	8 (9)	55 (14)	–2 (1)
Spring	–108 (140)	–6.0 (6)	–97 (16)	3 (1)
Summer	314 (130)	17 (5)	68 (14)	1 (0.3)
Fall	–249 (130)	–18 (5)	–33 (15)	1 (0.4)
Annual	1 (25)	1 (10)	–7 (4)	3 (0.6)

Note: Marginal effects calculated from ‘corrected coefficients’ in Table 16.4, columns (a) and (c). Marginal effects estimated using the climate of each observation. The mean and standard deviations calculated using bootstrapping (350 repetitions).

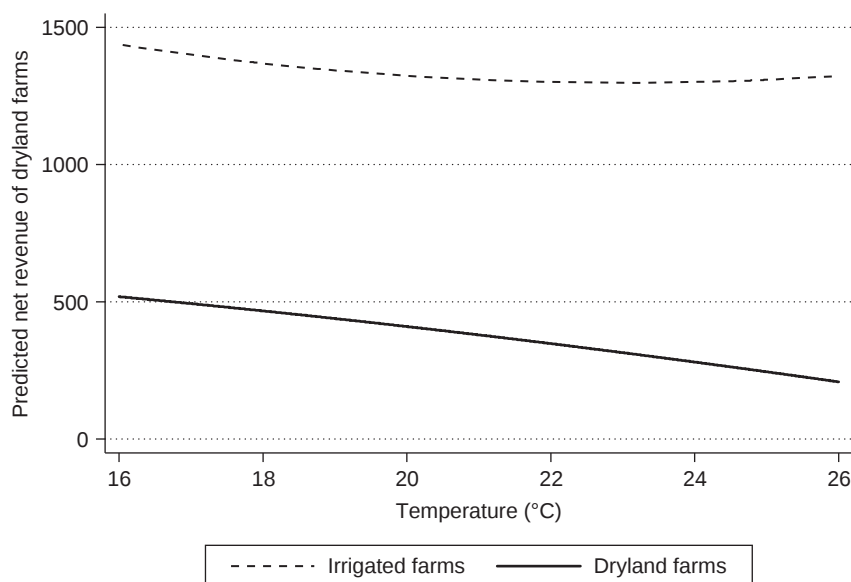


Figure 16.1 Temperature response functions of irrigated and rainfed farms (Africa analysis)

that vary at the national level, including agricultural policy, taxes, credit availability, trade and technology.

Climate Change Simulations

In this section, we calculate the welfare effect of a changing climate. The empirical analysis in the previous section was a cross-sectional comparison reflecting the performance of

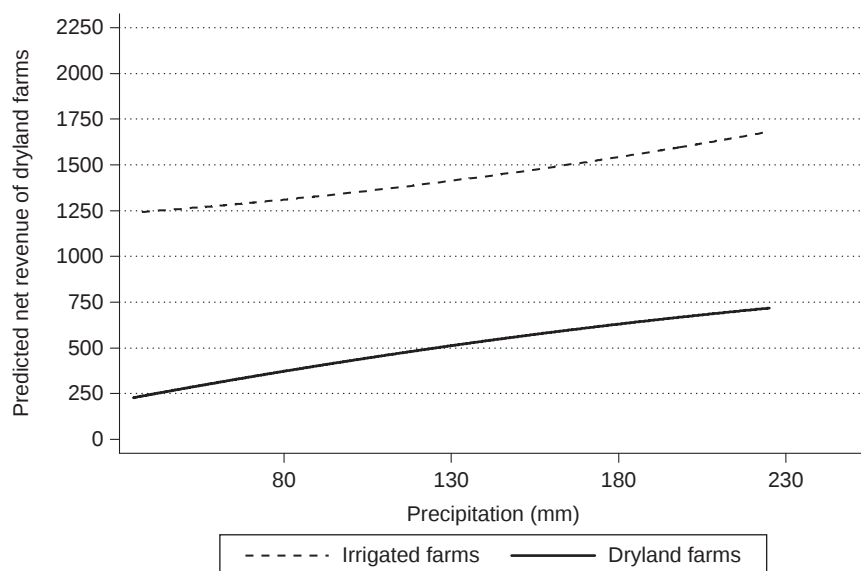


Figure 16.2 *Precipitation response functions of irrigated and rainfed farms (Africa analysis)*

one farm in one climate against another farm in a different climate. The forecast in this section uses these empirical cross-sectional results to project impacts over time. It must be understood that this exercise tries to measure long-term impacts and adaptations as farmers fully adapt to a new climate. The projections are not intended to trace dynamic adjustments from year to year.

We examine how alternative future climate scenarios may affect the choice of irrigation and net revenue per hectare. We rely on three climate models to provide a range of plausible predictions: the Parallel Climate Model (PCM) (Washington et al., 2000), the Center for Climate System Research (CCSR) model (Emori et al., 1999) and the Canadian Climate Centre (CCC) model (Boer et al., 2000). We look at predicted climate changes in each African country in 2100.⁵ On average, PCM predicts a relatively small increase in temperature (2.3 °C), CCSR is in between (4.5 °C), and the CCC model predicts a very large increase (6.5 °C) in temperature for Africa. The PCM predicts a slight increase in precipitation, especially in winter, whereas the CCC and CCSR predict slight reductions in precipitation.

For all the comparisons we assume that African agriculture remains otherwise unchanged. That is, we examine the impact of a future climate change scenario on current farms. In practice, farms will change over time. They are likely to have more variable inputs, more capital, new technology and better access to markets. All of these changes will probably have a large influence on future outcomes. It is important to recognize that the results in this chapter are not good forecasts of future outcomes, but simply forecasts of what role climate alone might play.

Non-marginal changes in climate may induce other changes, for example in prices. Exactly how prices will change is hard to predict because they will probably depend on

Table 16.6 Irrigation and welfare results across three climate change scenarios for 2100 (Africa analysis)

Irrigation	Exogenous OLS	Exogenous corrected	Endogenous (with flow constant)	Endogenous (with flow adjusting to climate)
Baseline income	483	483	483	483
<i>PCM scenario</i>				
Probability of irrigation (%)	16	16	56	44
Δ in expected welfare (\$/ha)*	65 (100)	44 (119)	169 (314)	115.5 (299)
Δ in expected welfare (%)	+13	+9	+35	+24
<i>CCSR scenario</i>				
Probability of irrigation (%)	16	16	13	13
Δ in expected welfare (\$/ha)*	-196 (53)	-206 (64)	-211 (68)	-216 (63)
Δ in expected welfare (%)	-41	-43	-44	-45
<i>CCC scenario</i>				
Probability of irrigation (%)	16	16	14	14
Δ in expected welfare (\$/ha)*	-263 (70)	-276 (75)	-278 (75)	-288 (68)
Δ in expected welfare (%)	-54	-57	-58	-60

Note: Standard deviation in parentheses calculated from bootstrapping. Exogenous calculation uses current irrigation probabilities and OLS or corrected conditional results. Endogenous calculation uses predicted future irrigation probabilities and corrected conditional results.

global production and demand. Although it is likely that African crop production will be reduced by warming, it is not at all clear that global production will be affected (Gitay et al., 2001). If market access in 100 years is good, the local price will be equal to the global price and there may be no price effects. If prices increase (decrease), farmers will gain (lose) and consumers will lose (gain). In this chapter we assume that there will be no price effects, so we might overestimate the impacts to African farmers.

Using the probit coefficients for irrigation, we first examine what happens to the probability of selecting irrigation in the two scenarios. In the PCM scenario, the seasonal temperature effects are largely offsetting. However, the large increase in winter precipitation encourages many farms to switch to irrigation. Ignoring the effects on flow, the probability of irrigation in the sample rises dramatically to 56 per cent (see Table 16.6). However, the large increase in winter flow actually has a negative effect on irrigation. When the change in flow is taken into account, the increase in irrigation in the PCM scenario is smaller (44 per cent). Note that new water storage facilities that could hold back winter flows and make them available in the spring and summer might convert harmful winter flows into beneficial spring and summer flows. We do not take different water management techniques into account in this analysis but they are potentially very promising. With the CCC and CCSR scenario, the seasonal temperature, precipitation and flow effects are offsetting, and the probability of irrigation falls slightly.

Multiplying through the probability of selecting irrigation times, the conditional income from irrigation and the probability of selecting rainfed agriculture multiplied by the conditional income of rainfed farming yields an expected income for each farm. The welfare effect per hectare is the average impact across the sample. Repeating this process in each climate scenario provides an estimate of the expected income in each scenario. The change in expected income is an estimate of the annual welfare effects of each scenario.

We compare four estimates of welfare effects for each climate scenario in Table 16.6. The first column presents the welfare effects assuming that rainfed and irrigated farms stay as they are now. That is, the probability of irrigation does not change and the conditional income can be estimated using OLS. The second model again assumes that the probability of irrigation does not change but it corrects for sample selection bias in the conditional income regression. The third column allows the probability of irrigation to adjust to climate change and it uses the corrected regression estimates. The fourth column allows the flow of water to adjust as climate changes as well. That is, the welfare estimates take into account estimated predicted flow based on climate change projections. Standard deviations were computed using bootstrapping (350 repetitions).

The first two measures of welfare are virtually identical. There is little evidence that sample selection bias is important in this case. However, the third and fourth columns with endogenous irrigation are different from the results of the first two columns. The exogenous estimates grossly underestimate the benefits of the PCM scenario because they do not take into account the large increase in irrigation permitted by PCM. The PCM scenario predicts a huge increase in irrigation along with the wetter and mildly warmer climate. Holding irrigation as it is today, the exogenous models predict that PCM would lead to only a small benefit of 9 per cent. Allowing irrigation to expand under the PCM scenario, the endogenous model predicts a benefit of 35 per cent. Even after adjusting for changes in flows, the endogenous model predicts a welfare benefit of 24 per cent under the PCM scenario.

The welfare results with the two hotter and drier climate scenarios are more alike across all measures. With the CCSR and CCC scenarios, there is not a large change in irrigation, so the exogenous welfare estimates are quite similar to the endogenous estimates. Furthermore, these hot and dry climate scenarios predict large losses. Without additional water, irrigation will not help farmers escape the very high temperatures of these scenarios. The importance of irrigation as an adaptation strategy thus depends upon whether there is an untapped water resource that can help farmers cope with climate change.

CASE B: ISRAEL

Israeli farmers have come to rely on technology and capital as substitutes for the scarce water and harsh climate they face. The combination of technology and capital has turned the warmer and potentially unproductive regions of Israel into highly profitable vegetable, fruit and flower farms (Fleischer et al., 2008).

Farmers in Israel use different technologies to increase their revenues and protect their crops from fluctuations in weather and climate conditions. These technologies

include different types of irrigation, different types of protected agricultural techniques (e.g. greenhouse, nets, plastic tunnels), hybrid varieties, hormones and other techniques. Irrigation and protected agriculture techniques are widely used. Almost all the crops, excluding some of the field crops, are irrigated and different types of protected agriculture techniques are used. Field crops are grown on large plots of marginal lands and depend on rainfall more than other crops.

Data

Data on Israeli farm operations were collected by conducting a face-to-face survey among a representative sample of farmers. The sampled farmers were chosen according to their location in the geoclimatic zones and type of village. The different types of rural villages define three strata that were represented proportionally in the sample. Three maps were created, each showing the geoclimatic zones of Israel: the first map denotes the location of the kibbutzim, the second the moshavim and the third the location of the other types of villages. We ordered the villages in each map from North to South in strata of 4 km each. All the villages in each stratum received a number identifying the stratum and were ordered according to their stratum number from North to South. Sampling within each stratum was done by systematic sampling. We chose one out of ten villages randomly from each stratum.

In addition, a total of 86 out of 863 rural villages in Israel were sampled: 41 moshavim, 31 kibbutzim and 14 others. Five farmers were chosen randomly from each moshav and other villages for the sample. In each kibbutz, five agricultural branches were randomly selected and the manager for that activity was interviewed for the survey. From each kibbutz, we analyzed five questionnaires, one for each activity. From each moshav and other villages we also analyzed five questionnaires, one for each randomly chosen farmer. A total of 381 farmers was interviewed, out of which 230 grew crops and the rest worked on animal husbandry farms. In this work we concentrated on crops and thus most of the analysis is conducted on the 230 farms with crops.

The survey asked numerous questions about farm characteristics, farmer characteristics, farm choices and farm outcomes. Table 16.7 summarizes key variables that were used in the analysis.

Temperature data for each farm were interpolated from 38 meteorological stations over the period 1965–79. Precipitation data were interpolated from 32 meteorological stations over the years 1961–90. Details on this interpolation method are available in Fleischer et al. (2008). The interpolation method calculates annual climate normals quite accurately.

Results

The different Israeli crops were divided into four subgroups: (1) fruit orchards; (2) flowers and garden plants; (3) field crops; (4) vegetables, potatoes and melons. The most intensively grown crops are flowers. Although only 1 per cent of the total land in the survey sample is used for growing flowers, they account for nearly 13 per cent of the total sample output⁶ (Table 16.8). All of the land used for flower growing is irrigated and 36 per cent of the flower farms employ different types of protected agriculture techniques

Table 16.7 Variable description and descriptive statistics (Israel analysis)

Name	Description	mean	s.d.
Experience	Experience of farmer or farm manager (years)	30.33	12.93
Farm size	Size of total crop land per farm (ha)	81.22	206.78
Cover	Percentage of covered land	0.30	0.44
Water quota	Yearly maximum irrigation water (m ³ /ha)	7371	5924
Latitude	Latitude	32.34	0.56
Longitude	Longitude	35.07	0.32
Altitude	Altitude (meters)	113.84	160.62
Temperature ¹	Average annual temperature (°C) 1965–79	19.40	0.85
Precipitation ¹	Average annual precipitation (mm) 1961–90	524.84	129.27
Sand2 ²	Sand with granule size 0.2 – 2 mm (% in soil)	4.28	2.54
Sand1 ²	Sand with granule size 0.02 – 0.2 mm (% in soil)	37.14	25.01
Salinity ²	Dummy = 1 if soil is not salt free	0.23	

Table 16.8 Distribution of agricultural output and crop land by type of crop and national and sample data (Israel analysis)

	Output value (%)		Crop area (%)	
	National ¹	Sample ²	National ¹	Sample ²
Fruit orchards	34.6	38.3	23.5	13.0
Flowers and garden plants	13.8	12.7	2.1	1.0
Field crops	12.2	25.7	49.3	77.8
Vegetables, potatoes and melons	39.4	23.3	25.1	8.2

Note: The main reason for the differences in the distributions is the definition of field crops and vegetables. At the national level vegetables are sometimes considered as field crops and vice versa.

Source: CBS (2005).

Table 16.9 Percentage of irrigated and covered crop area by type of crop (Israel analysis)

	Covered area (%)	Irrigated area (%)
Fruit orchards	10.7	100.0
Flowers and garden plants	36.0	100.0
Field crops	0.0	65.2
Fresh vegetables, potatoes and melons	8.3	100.0

(Table 16.9). Field crops are the least intensively grown crops. They are grown on 78 per cent of the land but account for only 26 per cent of the output value (Table 16.8). About two-thirds of the field crops are irrigated and none use protected agriculture techniques (Table 16.9).

This chapter looks at the use of irrigation and protected agriculture techniques by

Table 16.10 Percentage of each type of cover (Israel analysis)

Type of Cover	% from total covered land
Greenhouse	20
Net cover	65
Other	15

Table 16.11 Percentage of each type of irrigation (Israel analysis)

Type of irrigation	% of total irrigated land
Drip	54
Sprinkler	46
Other	17

Note: Percentages do not sum up to 100 since some of the farmers use a combination of irrigation systems.

Israeli farmers. Over 95 per cent of the farmers use irrigation. Israeli farmers irrigate 73 per cent of total cropland. About 31 per cent of all farmers use protected agriculture techniques for some of their crops. Within these two technologies there are different types of irrigation systems and coverings. Drip irrigation and sprinklers are the most popular type of irrigation systems (Table 16.10). Greenhouses can be used for heating and cooling, while net cover, the more ubiquitous type of cover, is used mainly to protect the crops from extreme climate conditions and prevent water evaporation (Table 16.11).

We now estimate what influences each farmer to choose each specific technology. We are particularly interested in whether climate influences adoption. If climate does affect adoption, the results would signal that the technology is an efficient climatic adaptation since farmers choose to use it to cope with their current climate. We estimate the amount of water each farmer uses for irrigation, the choice of irrigation technology and the demand for protected agriculture techniques.

We use an OLS regression to estimate water demand. Although we tested alternative functional forms, we found that introducing the climate variables in logarithmic functional form worked best. We also found that introducing the remaining variables in a linear functional form fit the data most closely. We regress water on the log of climate and a linear combination of the other independent variables. The results in Table 16.12 suggest that temperature does not have a significant effect on the water used by farmers. Although additional water can compensate for higher temperatures, farmers do not appear to actually change their water use for this purpose. In contrast, farmers do respond to having more precipitation by reducing water use. Of course, this was expected since water is expensive and additional precipitation implies that less water is needed to maintain soil moisture. The only other variable that was significant in Table 16.12 was farm size. Larger farms tend to use less water per hectare. Large farms use less water because they tend to grow lower-valued field crops on more marginal land. Note that farmer characteristics are not significant.

In Table 16.13, we use a probit model to examine the choice of specific types of irrigation technology. Drip irrigation is more likely to be used in hotter climates. Precipitation

Table 16.12 *Irrigation water demand model (Israel analysis)*

	Coefficient	Std. err.
Constant	39.83	41.59
Ln (temp.)	-2.47	11.25
Ln (prec.)	-3.986*	2.023
Sand1	0.0230	0.0206
Sand2	-0.1261	0.1677
Salinity	1.209	1.125
Farm size	-0.0098*	0.0019
Experience	-0.0161	0.0317
Water quota	0.0730	0.1573
R^2	0.14	

Note: * Denotes 5% significance.

appears not to influence the choice of sprinklers. Drip irrigation is, however, more likely to be used on sandy soil but less likely if the soils are saline. Sprinklers are more likely to be used in cooler locations with less rainfall and are less likely to be used on sandy soils. Other types of irrigation are more likely to be used in hotter and wetter locations. Other irrigation is also more likely if the soils are sandy.

Our final analysis examines the choice of protected agriculture techniques (Table 16.14). We use a two-equation selection model of cover that first estimates whether protected agricultural techniques are used at all, and then estimates the fraction of cropland covered. Maximum likelihood estimation (MLE) is used to estimate both equations: the binary selection equation and the percentage of cropland placed under protected agricultural techniques for farmers that chose to cover. Higher temperatures increase significantly the likelihood that a farmer will adopt cover. Cover is used in Israel to moderate high temperatures and prevent water evaporation. Land that is covered is also irrigated. The areas with the high levels of precipitation are mountainous areas. Farmers cannot allocate large plots of land for field crops as is done in the flatter areas. They will grow plantations which they can irrigate and protect by covering. The size of the farm and the number of years since establishment are negatively correlated with the decision to cover.

Although climate influences the choice to cover, it does not influence the fraction of cropland a farmer chooses to cover. The fraction of cropland that is covered is a function only of the size of the farm. The larger the farm is, the smaller is the share of the covered area forming the total size of the farm. This stems from the fact that large farms allocate most of their land to growing field crops.

Climate Change Simulations

We simulated in this section the effect of three different climate scenarios on our dependent variables: demand for water, likelihood of choosing different irrigations systems and the percentage of covered land (Table 16.15). We use the same climate models as the African case for 2100. On average PCM predicts 3.20 °C increase in temperature and 11 per cent change in precipitation, CCSR predicts 5.80 °C increase in temperature and

Table 16.13 Probit model of irrigation technology choice (Israel analysis)

Drip				
Variable	Coeff.	Std. err.	Marginal effect	Std. err
Constant	-17.59	11.72	-4.33	2.85
Ln (temp.)	5.58**	3.30	1.37**	0.80
Ln (prec.)	0.0152	0.5047	0.0037	0.1242
Sand1	0.0091**	0.0053	0.0022**	0.0013
Sand2	-0.0944**	0.0518	-0.0232**	0.0126
Salinity	-0.447	0.3009	-0.0969**	0.0562
Farm size	0.0009*	0.0004	0.0002*	0.0001
Experience	0.0080	0.0083	0.0020	0.0020
Water quota	-0.0338	0.0413	-0.0083	0.0102
Sprinkler				
Variable	Coeff.	Std. err.	Marginal effect	Std. err
Constant	23.4828*	10.6762	7.4867*	3.3774
Ln (temp.)	-5.763*	2.978	-1.837*	0.943
Ln (prec.)	-0.872	0.482	-0.278	0.153
Sand1	-0.0153*	0.0052	-0.0049*	0.0016
Sand2	0.0467	0.0418	0.0149	0.0133
Salinity	0.1033	0.2915	0.0323	0.0892
Farm size	-0.0006*	0.0004	-0.0002*	0.0001
Experience	-0.0042	0.0077	-0.0014	0.0025
Water quota	0.0404	0.0391	0.0129	0.0124
Other irrigation				
Variable	Coeff.	Std. err.	Marginal effect	Std. err
Constant	-30.408*	12.060	-7.793*	3.027
Ln (temp.)	6.714*	3.306	1.721*	0.835
Ln (prec.)	1.478*	0.561	0.3789*	0.1412
Sand1	0.014*	0.006	0.0036*	0.0015
Sand2	0.000	0.043	0.0000	0.0111
Salinity	0.313	0.310	0.0865	0.0913
Hectare	0.001	0.001	0.0002	0.0001
Experience	-0.001	0.009	-0.0003	0.0022
Water quota	-0.050	0.045	-0.0128	0.0115

Note: * Denotes 5% significance.

-23 per cent change in precipitation and CCC predicts 5.60 °C increase in temperature and 1 per cent change in precipitation. We also assumed that Israeli agriculture remains otherwise the same. We can see in Table 16.10 that under PCM and CCC, which predict increase in temperature and precipitation, the demand of irrigation water is declining. In

Table 16.14 Two-equation demand model for protected agriculture techniques (Israel analysis)

	Selection equation	
	Coefficient	Std. err.
Constant	-27.7906*	12.5036
Ln (temp.)	7.7379*	3.4417
Ln (prec.)	0.8028	0.5485
Sand1	0.0215*	0.0054
Sand2	0.0240	0.0427
Salinity	0.1137	0.3011
Farm size	-0.0056*	0.0013
Exp	-0.0272*	0.0083
Swater	-0.0734*	0.0408
	% of land in cover	
	Coefficient	Std. err.
Constant	-0.4838	3.8200
Ln (temp.)	0.4017	1.0937
Ln (prec.)	-0.0094	0.1704
Sand1	0.0024**	0.0014
Sand2	-0.0049	0.0125
Salinity	0.0984	0.1295
Farm size	-0.0023*	0.0005
Sigma(1)	0.2860	0.0341
Rho(1,2)	0.4935	0.2273

Note: * Denotes 5% significance and ** denotes 10% significance.

Table 16.15 Demand for irrigation water, choosing type of irrigation and percent of covered land across climate scenarios (Israel analysis)

	PCM 2100	CCSR 2100	CCC 2100
Change in demand for irrigation water (% per hectare)	-11.2	2.4	-10.0
Δ in the probability of using sprinklers	-32.7	-47.4	-52.2
Δ in the probability of using drip	22.6	40.8	39.5
Δ in the probability of using sprinklers or other methods of irrigation	32.4	42.9	50.0
Δ in % of covered land	6.4	12.1	11.5

comparison, under CCSR the demand for water is increasing due to the predicted drastic drop in precipitation. Simulations also show that under all climate models farmers will move from sprinklers to the more efficient drip irrigation and use more cover. The simulations show that farmers change their use of technology with climate change.

CONCLUSIONS

We show that use of technology in agriculture is responsive to climate change in two different world regions, Africa and Israel. By building a two-stage selection model for the African case we reveal that if climate changes, it is very likely that the pattern of irrigation across Africa will also change. That is, irrigation is endogenous to climate change. In the Israeli case we regress the use of irrigation water, the adoption of irrigation technology and the use of cover on climate and other independent variables in a cross-sectional analysis. We find that Israeli farmers use irrigation and cover to compensate for dryness and excess heat. Since farmers adapt to the conditions they live in, the study shows that use of technology is sensitive to climatic conditions.

These results are very promising for countries that may face future harsh climate conditions as a result of global warming. The fact that farmers in both regions use different technologies in different climatic conditions shows that this can be applied universally as a strategy for mitigating potential harmful effects of climate change. We suggest that farmers have some capital-intensive high-technology options to adapt to climate change; we see it in less technologically developed Africa and in highly technologically developed Israel. These new options will help future farmers raise their net incomes to help offset the negative impacts of global warming.

However, it should be noted that in the Israeli case, in addition to the technological level of agricultural production, there is a well-developed support system for farmers. There are a few R&D centers that do agricultural extension providing information transfer, access to capital and access to markets. The access to European markets is pivotal to the profitability of the Israeli agricultural sector. This stems from the use of irrigation, cover and other technologies in hot climate regions that enables them to adjust to the high temperatures. As a result they are the first to bring their produce to both the local and European markets and thus enjoy high prices before their competitors' outputs reach the markets.

It is also should be taken into consideration that low-cost technologies may be more attractive in less developed countries. Farmers in many developing countries may not be able to afford high-cost alternatives. Governments and development institutions should examine what are the effective adaptation technologies in each region of the world. They then need to explore whether farmers can adopt these technologies as climate changes. By providing an appropriate combination of financial support and information and technology transfer, governmental agencies may be able to provide valuable assistance to farmers as they adapt to climate change.

Finally, the chapter makes it clear that that adaptation is important. There are different adaptation strategies important to farmers including switching crops (Kurukulasuriya and Mendelsohn, 2008b; Seo and Mendelsohn, 2008b) and livestock species (Seo and Mendelsohn, 2008a). It is important to learn more about what farmers can do to cope with climate change so that we can understand how best to facilitate adaptation. Understanding adaptation is also critical if we are to make accurate predictions of the net impacts of climate change.

NOTES

1. Land uses themselves are influenced by climate and other variables (Mendelsohn et al., 1996). However, this topic is beyond the scope of this chapter.
2. We are deeply grateful to the country teams from each of these countries for designing, collecting and cleaning these data and making this project a success. For more information about the entire study, see Dinar et al. (2006).
3. Available upon request from the authors.
4. The results of the marginal analysis with clustering can be obtained from the authors.
5. The choice of 2100 as a scenario is for exposition purposes. The analysis can easily project impacts for other scenarios.
6. It was not possible to calculate profits per crop since some farmers grow a few crops and it is impossible to separate costs according to crop type. Therefore we used output value in the data description.

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APPENDIX A

Table 16A.1 Temperature (°C) normals (sample means) – Africa analysis

Country	Winter	Spring	Summer	Fall
Burkina Faso	23.6	28.3	28.9	24.5
Cameroon	19.4	21.4	20.0	18.9
Egypt	11.7	13.2	24.1	23.4
Ethiopia	18.6	21.5	19.7	18.1
Ghana	21.8	24.8	22.6	21.2
Kenya	18.8	19.7	18.4	19.1
Niger	26.3	30.8	33.9	29.2
Senegal	24.5	29.1	31.5	26.7
South Africa	11.5	15.5	20.7	19.4
Zambia	16.7	21.7	21.1	19.6
Zimbabwe	16.6	21.3	22.5	20.6
Total	19.8	23.4	24.5	22.2

Note: Seasonal climates have been adjusted so that they are consistent regardless of hemisphere.

Table 16A.2 Precipitation (mm/mo) normals (sample mean) – Africa analysis

Country	Winter	Spring	Summer	Fall
Burkina Faso	2.6	15.8	113.8	133.1
Cameroon	60.3	101.9	185.1	228.6
Egypt	12.8	7.0	2.3	3.5
Ethiopia	19.4	49.2	123.7	117.5
Ghana	30.9	59.7	112.4	111.7
Kenya	88.4	103.0	84.3	60.0
Niger	0.8	3.2	64.1	70.6
Senegal	2.2	1.1	47.9	112.7
South Africa	1.8	55.0	86.4	68.8
Zambia	48.3	57.7	108.6	100.7
Zimbabwe	7.5	15.4	138.8	90.0
Total	25.9	39.8	96.1	102.4

Note: Seasonal climates have been adjusted so that they are consistent regardless of hemisphere.

Table 16A.3 Flow (million mm³/mo) normals (sample mean) – Africa analysis

Country	Winter	Spring	Summer	Fall
Burkina Faso	0.03	0.01	0.04	0.11
Cameroon	0.32	0.23	0.67	1.21
Egypt	3.08	2.66	7.60	11.17
Ethiopia	0.11	0.11	0.45	0.63
Ghana	0.23	0.13	0.47	0.95
Kenya	0.12	0.16	0.21	0.16
Niger	0.20	0.07	0.47	1.23
Senegal	0.07	0.01	0.15	0.51
South Africa	0.02	0.02	0.06	0.06
Zambia	0.41	0.16	2.40	2.92
Zimbabwe	0.12	0.09	0.52	0.61
Total	0.43	0.33	1.18	1.78

17 Climate change and technological innovation in agriculture: adaptation through science

Douglas Gollin

INTRODUCTION

As global climate change proceeds over the decades ahead, its effects on human welfare will depend crucially on the ability of agricultural science and technology to respond to changes in temperature, rainfall patterns and other dimensions of climate change. Is it possible to develop crops, animal breeds and production systems that respond to the challenges of climate change? Or will the complexity of climate-related problems exceed the capacity of the agricultural research system? Can researchers develop technologies that reduce the costs of adaptation? If so, what are the time constraints on developing the necessary technologies? And what levels of investment might be needed? What will happen to those countries with low research capacity at present? Can the agricultural science responses to climate change be centralized in some vast international project? Or will research capacity need to be developed at much more local scales?

The goal of this chapter is to explore the above questions, building on what the literature tells us about the organization and impact of past investments in agricultural science and technology. Much of the chapter is speculative, in the sense that it attempts to sketch out the directions in which the frontiers of agricultural technology might plausibly be expected to move over the next hundred years or more. Given the failures of past efforts to forecast technology, this is an undertaking that is daunting, to say the least. The chapter also focuses on poor countries, where agriculture accounts for far larger shares of employment and output than in rich countries. The world's poor countries in general are also more susceptible to climate change impacts, and many poor countries have less well-developed research infrastructure.

This chapter is divided into five sections. The next section sketches out some of the different avenues for research, emphasizing that genetic improvements are only one of the areas in which science and technology can address the challenges of climate change for agriculture. Then a section discusses the current industrial organization of agricultural research and the ways in which that organizational structure may shape the responses of the international research system; it will also touch on some of the shortcomings of the current system. A further section focuses on the magnitude of the investments in agricultural science and technology that may be needed in addressing climate change and relate this to current levels and trends of investment. The final section offers a few observations on the particular challenges that are likely to beset the scientific response to climate change adaptation in agriculture.

AVENUES FOR RESEARCH

In contemplating technological responses to climate change for agriculture, much discussion has focused on the role of plant breeding and crop science. For example, the Gates Foundation's support for agricultural science and technology, which has totaled almost half a billion dollars since 2006, has gone largely into these areas (Bill and Melinda Gates Foundation, 2009). Similarly, Lybbert and Sumner (2009) begin their survey of agricultural technology responses to climate change by examining the potential for 'new traits, varieties, and crops'.

Interventions in the area of plant science might include research to develop heat-tolerant or drought-resistant crop varieties, or alternatively, flood-tolerant plants for areas likely to experience increased exposure to heavy rains and rising rivers. There might also be a role for varietal technologies that will address the new biotic stresses that will probably emerge with climate change, such as insects, plant diseases and new weeds. There are undoubtedly many opportunities to use plant science and breeding to enhance climate adaptation, drawing on both traditional plant breeding techniques and the newer potential for the introgression of genes from novel sources.

However, crop genetic improvement is only one of a number of avenues along which technological innovation could occur. Agricultural research also encompasses areas such as agricultural engineering, plant physiology, soil science, information technology and many others. Climate change adaptation will depend on advances in many of these areas, as pointed out in recent reports by scholars associated with the Consultative Group on International Agricultural Research (CGIAR Challenge Program on Climate Change, Agriculture, and Food Security, 2009; Vermeulen et al., 2010). It would be a mistake to assume that the most valuable adaptation technologies will be new seeds; there may in fact be other research strategies that prove to have higher payoffs. The history of agricultural science over the past 50 years teaches us that plant and animal breeding are outstanding tools for achieving certain goals, but they are very blunt instruments for other purposes. Perhaps the best responses to climate change will come from modification of production systems rather than from developing heat-tolerant and drought-tolerant varieties and breeds.

This section reviews a few of the possible directions for agricultural science and technology. There are many potential avenues for climate change adaptation, and breeding is only one possible pathway to adaptation.

Breeding and Genetic Improvement

Plant and animal breeding have generated enormous impacts on agricultural output and human welfare over the past century. Breeding includes traditional methods of genetic manipulation – crossing (hybridization) and selection – along with newer molecular techniques such as tissue culture, genetic modification and marker-assisted selection, for example. In all cases, the goal is to develop breeds, varieties or individuals with superior genetic potential.

Plant breeding for climate adaptation

As noted above, scientists have a large toolkit for addressing climate adaptation, with new scientific discoveries opening up opportunities at a rapid pace. To what extent can

these discoveries help with climate adaptation? One message that emerges from the recent literature is that there may not be a clear line between plant breeding for climate adaptation and breeding for yield enhancement. Araus et al. (2008) point out that water availability is one of the main limits to crop yield, in general; in this sense, research that targets drought stress and heat tolerance is likely also to have impacts on yield potential.

Some of the technologies currently attracting the greatest attention are those with direct relevance to climate: heat tolerance, drought tolerance and resistance to emerging disease and pest problems linked to climate change. It seems likely that over the next several decades scientists will be able to make substantial progress with respect to many of these traits. At the same time, however, history cautions us to bring some skepticism to the notion that climate adaptation can be achieved simply with a few tweaks to existing crop germplasm. Some of the traits desired for adaptation to climate change have in the past proven remarkably elusive. A general problem is that many such traits involve multiple genes and quantitative trait loci (QTLs), so that entire segments of DNA must be transferred. This is far more complicated than moving single genes (such as the semi-dwarfing genes that sparked the Green Revolution advances in rice and wheat). Moving the desired genes is often difficult without also picking up a certain amount of undesirable DNA that lies between the desired loci.

A difficulty in plant breeding for heat and drought tolerance has been that it is difficult to select for advantageous characteristics because they are not well observed at the level of individual plants. Instead, researchers have tended to select for physiological properties that are thought to be related to good performance. Araus et al. (2008) describe an alternative approach, in which breeders can focus on 'secondary characteristics', which are easily observed phenotypic attributes correlated with good performance under heat and drought stress. By focusing on these secondary characteristics, or even on molecular markers that are related to secondary characteristics, breeders can more quickly screen large numbers of plants for desirable genetic attributes. This helps with the selection of material for breeding programs; however, the selection and breeding processes remain challenging.

The bottom line is that some traits, apparently including many of those desired for climate adaptation, are difficult to manipulate. Breeding for these traits will not be easy. Over a period of decades, with ever-increasing understanding of the molecular underpinnings of plant physiology and morphology, it seems likely that scientists will eventually succeed in achieving a high degree of climate adaptation. However, there may be tradeoffs between the traits desired for adaptation and those desired for other properties desired by consumers and producers.

To give one example, scientists have been seeking drought-tolerant rice varieties for over 20 years. Measured in terms of scientific understanding, the progress has been impressive. The mechanisms of drought tolerance are far better understood than they were in the early days of modern rice research. Many varieties have been identified that display morphological or physiological properties that make them relatively good at withstanding drought stress. Drought-tolerant varieties may have deep root systems or waxy coverings on leaves, or they may display 'leaf roll' that allows them to tolerate dry conditions. However, these traits are not always governed by a single trait that can be inserted on top of an existing variety. Instead, these properties may be linked to multiple genes. Researchers have identified large numbers of QTLs that appear to code

for drought-tolerance characteristics. There are often also substantial genotype-by-environment ($G \times E$) interactions, so that these characteristics are not displayed under all circumstances. As a result, drought tolerance is often accompanied by noticeable changes, perhaps undesirable, in other phenotypic characteristics. Thus the challenge to date has been less that drought tolerance itself is unattainable; instead, the difficulty has been breeding drought-tolerance varieties that will be adopted by farmers.¹

Similar stories relate to the efforts to develop maize varieties that will withstand heat stress. Research has shown that heat stress itself is an enormously complicated phenomenon, and scientists have dramatically increased their understanding of the mechanisms through which heat can impact crop yields (and crop survival). Heat can affect plant physiological responses (e.g. by causing wilting) which may in turn affect the leaf area available for photosynthesis. Hot weather may also induce plants to mature faster and to bear seeds faster, presumably by triggering certain genetically linked switches. Early maturation in turn reduces the number of days (hours) in which a plant can gather energy through photosynthesis, which in turn impacts yields. Understanding these mechanisms of heat stress can point scientists towards possible breeding interventions, but actually developing heat-tolerant varieties that perform well in farmers' fields is a more complicated problem.

Plant breeding for other objectives

Breeding directly for climate adaptation may be difficult, but in the long run it seems likely to prove successful. It is not obvious, however, that this is the best way in which crop genetic improvement efforts can address the challenges of climate change.

Moreover, genetic improvements that do not target climate-related traits may be more valuable than improvements that are narrowly focused on climate adaptations. Technologies such as tolerance to heat, drought or flooding are essentially designed to reduce the variance in crop yields. Clearly farmers value yield stability. However, they also value high mean yields. In fact, past experience shows that farmers are often willing to trade off a substantial amount of yield stability in order to get higher mean yields. Arguably, much of the experience of the Green Revolution indicates a corresponding willingness to swap low-yielding (but low-variance) traditional varieties for high-yielding varieties (HYVs), even when the higher-yielding varieties have relatively high variance.²

This suggests that the greatest welfare contributions of crop genetic improvement over the next century might come from seeking continued productivity gains, rather than worrying unduly about the vulnerability of crops to weather shocks. Some evidence suggests that yield increases and intensification may in turn lead to mitigation of climate change impacts (Burney et al., 2010). Given adequate access to markets and sensible policies, the forces of trade and exchange should make it possible to mitigate the effects on consumers of local weather-related variations in production. Farm income might fluctuate widely with greater climatic variability; but mechanisms such as rainfall insurance or temperature insurance might offer farmers protection from income shocks, and might do so more effectively than new crop varieties. Farmers have access to a wide range of other formal and informal vehicles for smoothing income, including both *ex ante* and *ex post* actions. Perhaps they do not need crop varieties that reduce weather losses so much as they need varieties with higher yield or lower unit costs of production.

Thus the priorities for crop genetic improvement might be yield potential (which might be increased by altering the photosynthetic pathways of rice and wheat, for example; or through changes in the plant architecture that would maximize the photosynthetic efficiency by capturing more of the available sunlight). Disease and pest resistance will also remain important objectives for plant breeding, although clearly the pest ecology will change as climate changes. Tolerance of various abiotic stresses such as aluminum toxicity and iron toxicity will remain important objectives. And perhaps, as climate change shifts cropping zones farther away from the equator, shorter-duration crop varieties might have an important role to play in allowing crops to 'migrate' to higher latitudes. Although research in these areas will not necessarily be seen as promoting adaptation to climate change, it is possible that the social value of such research may prove higher than efforts to 'climate-proof' existing crop varieties.

Animal breeding for climate adaptation

Although genetic improvement in agricultural crops seems to garner more attention, there are similar opportunities to improve productivity and adaptation in animal agriculture. Genetic improvement has been an enormously important source of productivity gains in animal agriculture over the past century, particularly in poultry and pig production as well as in commercial dairying. Animal genetic resources have been developed in conjunction with new production systems to maximize the physical and financial efficiency with which feed is converted into animal products. By improving feed conversion efficiency through genetic improvement, farmers benefit both from reducing feed costs per unit of output and also from reducing capital costs.

Because animal agriculture is a significant contributor to greenhouse gas emissions, one major focus of animal science over the next several decades will be ways to mitigate or reduce the climate impacts from this sector. This has been the subject of a number of recent studies (e.g. Steinfeld et al., 2006; Steinfeld and Gerber, 2010). Increasing the productivity of ruminant systems will allow for reductions in emissions per unit of output. There is some evidence also that consumption is shifting away from ruminant-based products, such as red meats, and into the products from monogastric animal systems (e.g. poultry and swine). This will also tend to reduce emissions. However, this chapter focuses on the research system's potential role in climate adaptation, rather than its role in emissions reduction. Detailed reviews of this topic can be found in Hoffmann (2010).

In terms of adaptation, climate change will pose significant challenges for intensive animal agriculture. Heat stress can kill animals in confined systems and it also reduces their ability to eat and to digest food. Cattle and other ruminants are particularly affected by heat stress, since their digestive systems utilize fermentation processes that generate heat. When ambient air temperatures are too high, it can interfere with the digestive processes of ruminants, leaving them unable to disperse heat effectively and, in turn, reducing the quantities of feed that they can process.

Genetic improvement can offer some useful strategies for addressing heat stress in animals that are kept in intensive production systems. Bianca (1961) noted that heat tolerance in cattle could be affected by numerous phenotypic characteristics that are susceptible to breeding, such as baseline body temperature, hair texture and color, and surface/mass ratio. There also appears to be significant variation at the level of individual

animals in variables such as feed efficiency, which may also affect their heat sensitivity (Arthur et al., 2004).

However, although breeding and selection have for many centuries been the principal ways in which animal agriculture has adapted to climate and environmental conditions, there has been another widespread approach: modification and control of the production environment itself. Because animal agriculture is a relatively high-value activity, and because it can be spatially concentrated, many forms of animal agriculture lend themselves well to production under controlled conditions.

For example, intensive animal production systems in hot places can make use of sprinkler systems, fans and 'mist cooling' systems to generate evaporative cooling at modest cost. These systems are widely used to relieve heat stress on animals and have proven economical in both dry and humid environments. Such interventions will be discussed in greater detail below, but the emerging consensus is that genetic improvement in animal agriculture will be highly complementary with changes in production systems (e.g. Collier et al., 2006; Lin et al., 2006).

Thus, poultry breeding will continue to focus on developing genetic types, such as breeds with naked neck (Na) genes or frizzle (F) genes that thrive in high-intensity confinement systems. Dairy breeding may similarly focus on cattle breeds (e.g. Holstein-Friesians) that produce at high levels in intensive systems. To the extent that production systems of this kind are likely to grow in importance in future, as a response to both climate change and to market conditions, breeding will continue to target these controlled environments rather than targeting climate adaptation directly.

One caveat to this is that today's intensive systems have often required some modification as they have been transplanted to tropical environments and other locations that differ from the temperate-zone locales where they originated. Although the tendency has been to design production systems in which high-productivity genetic types can thrive, this may become more challenging as intensive production systems spread still further into geographic areas with extreme climates and as climate changes in the areas where intensive systems are now established.

Modification of Farm Practices

In addition to changes in the genetics of crops and livestock in use on farms, there is broad scope for modification of farm practices to adapt to climate change. Some of these changes will be initiated and explored by farmers themselves, who are likely to work out optimal responses to climate change related to planting and harvesting dates, the timing of various farm activities, responses to carbon fertilization, changes in irrigation schedules and so forth. Farmers have historically been remarkably capable of modifying their practices to deal with short-term changes in climate as well as in adapting their practices when they move to locations with markedly different terrain and climatic conditions. To the extent that farmers understand the technologies that are available to them, there may be little role for formal 'research' aimed at this class of practices.

In some cases, however, farmers may lack sufficient information to adapt their practices to new climatic conditions. One such situation would be the case in which climate change happens quickly without leaving farmers much time to experiment. Another would be the case in which new conditions are dramatically different from previous

conditions – in other words, situations in which production regimes switch altogether. These changes are much harder for farmers to manage than minor adjustments or fine-tuning of existing farming systems. For example, farmers may have little experience or knowledge of entirely new crops, especially those with exacting requirements. Work by Conley and Udry (2010) on pineapple in Ghana, and by Bandiera and Rasul (2006) in Mozambique suggests that farmers may have considerable difficulty working out the details of cultivating entirely new crops. In such cases, it may be valuable to have researchers who can work out the profit-maximizing production techniques for a particular locale (sometimes referred to as a ‘recommendation domain’).

Modification of Production Environments

As noted in the previous section, another dimension of agriculture’s adaptation to climate change will be the use of controlled production environments in which climate effects on production are reduced or eliminated, at least under normal circumstances. Such controlled conditions have become common in the industrial agriculture of rich countries in the twenty-first century, where many types of agriculture have essentially taken on the characteristics of industrial production. Control of the environment arguably reaches its apogee in modern concentrated animal feeding operations (CAFOs), in which animals are kept under varying degrees of confinement and all aspects of the production system can be managed, including temperature and humidity. However, similar modes of production have become commonplace in horticulture, with the most extreme example being hydroponics and greenhouse modes of production, but also encompassing ‘protected agriculture’ or ‘plasticulture’ techniques in which plastics and other coverings are used to cover both soil (or other growing medium) and plant rows. These techniques are in wide use for cut flowers, lettuce, tomatoes, peppers, cucumbers, melons, strawberries and a wide range of other crops. They are not, however, used currently on grain crops or other bulk commodities that have relatively low values per unit of land under production.

As will be discussed below, technologies for environmental control may well become more ubiquitous under conditions of rapid environmental change. These technologies may also prove more valuable than genetic improvement, or at the very least, the pace and direction of genetic improvement will be linked to technological progress in the management of production systems. This is already true in animal agriculture, and to an increasing extent it is likely also to be true in crop agriculture, at least in rich countries.

A limitation of these technologies is that they cannot readily be used for land-intensive crops that require large amounts of space. Bulk grains and staple food crops, including roots and tubers and other starch staples, currently account for the vast majority of the world’s cropped area. The sheer scale of production suggests that ‘protected agriculture’ is not likely to be economically viable except in rare instances. Most of the world’s wheat, maize and rice will not be grown in greenhouses or under plastic row covers. The closest plausible approximation to this kind of protection is that irrigation investments may have high payoffs under conditions of climate change, and the proportion of staple food crops grown under irrigation could change, especially if the technologies for irrigation can be improved so that the costs of installing and operating irrigation will fall. This issue will be discussed in the next section.

Water Control and Water Use Efficiency

For bulk crops, the main way in which producers can alter the physical production environment to adapt to climate change is through greater water control and improved management of water supply. Greater investment in irrigation systems and expansion of irrigated areas will certainly play a role in climate adaptation, since water availability is a crucial determinant of plant physiological responses to heat and drought.

For the most part, expansion of irrigation falls outside the scope of this chapter since it represents a form of investment rather than technological improvement. However, there is currently a large amount of research aimed at improving technologies that allow for greater ‘crop per drop’ – effectively the technological efficiency of water use. Many disciplinary approaches are involved in this research.

From the engineering side, new computer-aided systems carefully monitor water flow and allow for more precise management of the timing and flow of water using sensors and programs that allow farmers to fine-tune application of water at a highly localized spatial scale. This is a far cry from traditional ‘on–off’ techniques in which fields are flooded periodically. Another approach is to manage the materials used in irrigation canals and pipes. New sensors, control techniques, computing power and improved crop models allow for real-time adjustment of water inputs so that precisely the right quantities of water can be delivered to plants at the moments when it will have maximum marginal impact on crop yields.

Beyond these high-tech approaches to water control, there are a number of simple and inexpensive technologies that involve water capture – for example, through contour plowing, ditches and drainage techniques, green manuring and recycling of runoff and waste water. These can increase the amount of rainfall available for crops and the retention of soil moisture. Often, these measures provide simple alternatives to more expensive irrigation installations.

Another direction in which water management technologies can help with climate adaptation for agriculture is through treatment technologies. For example, techniques that reduce salinity are already in advanced stages of development, as is a variety of techniques for treating and managing waste water.

Engineering and Mechanical Innovations

Although their contribution has been obscured by the crop genetic technologies that were central to the Green Revolution, mechanical innovations have also had enormous productivity impacts over the past several decades on agriculture in the developing world. The introduction of lightweight trucks, small tillers and simple mechanical seeders have together had a huge impact on rice cultivation in many parts of Asia. These mechanical innovations have allowed for the release of labor from farming and have driven down costs to producers. Although these technologies are not directly linked to climate adaptation, they give some sense of the scope for simple and low-cost improvements in mechanical technology in agriculture.

High-efficiency foot pumps and diesel pumps have made it possible for farmers to create small-scale systems for water harvesting and irrigation. Similarly, there have been advances in the manufacture of low-cost PVC pipe for drip irrigation and plastic storage

tanks for water harvesting. In rural electrification, too, technological advances have radically changed the available options for rural households, from hand-cranked generators for lights and radios to low-cost biogas digesters that are sufficient to power small agro-processing facilities. These technologies will not necessarily facilitate production adaptations to climate change, but by increasing (and perhaps diversifying) farm income, they may allow for economic adaptation. Since climate change may alter local agricultural production more than it alters global production, thus affecting the geography of agriculture, this kind of economic adaptation will be critical. Some rural households may lose the ability to produce their own food adequately, and households that are now able to sustain themselves may turn into net purchasers of food. For these households, economic adaptation will be crucial. They will need to find new sources of income and new ways of adding value to farm production that can enable them to purchase the food they need. Engineering and mechanical technologies may play an important role in this kind of adaptation.

Chemical Discovery and Chemical Use Efficiency

Another area of innovation will be in the discovery of new chemical fertilizers, pesticides and herbicides that will alter the production possibilities open to farmers. In some cases, chemical technologies can directly affect water conservation and climate adaptation, albeit in non-obvious ways. For example, herbicides have made possible no-till or low-till agriculture in many parts of the developing world. It is often claimed that no-till techniques allow farmers to increase the organic matter content and water retention capacity of their soils. Herbicides can also reduce the water lost through evapotranspiration by weeds, thus retaining more soil moisture for crop plants.

Improved chemical fertilizers and chemical soil amendments of various kinds can also allow farmers to grow crops in areas previously thought of as infertile. This may be important as climate change alters the geography of agriculture further. For example, the widespread use of chemical amendments to address problems of iron and aluminum toxicity opened up the Brazilian *cerrado* for cultivation of soybeans and other crops.

Pesticides will allow farmers to address the problems ensuing from the emergence of 'new' insects and diseases; especially in rich countries, pesticides and fungicides will play an important role in enabling farmers to respond to intensified pressure from a variety of biotic stresses.

Similarly, animal agriculture will rely on a range of new drugs and pharmaceuticals that allow for production under conditions of greater heat, and again for the problems of emergent diseases and pests.

Summary

Across a vast range of agricultural technologies, innovation will alter the options that are available to farmers, in many ways that cannot be fully anticipated at this point. We have very limited capacity to forecast the technological advances that will characterize the next century. Today's agriculture would look fantastic, in the literal sense of the word, to farmers at the start of the twentieth century, when even rich countries were dominated

by small-scale modes of production, and animal traction was in wide use throughout Europe and North America. Antibiotics were unheard of and veterinary treatments were rudimentary at best. Mendelian genetics had been only recently rediscovered; with so little understanding of biology, little systematic plant breeding took place. The world food system struggled to meet the needs of a global human population of 1.5 billion, and malnutrition led to the systematic stunting (as we understand it today) of most of the world's population.

Forecasts of future agricultural production have consistently underestimated the potential of new technologies to increase production and to expand the areas suitable for farming. Although we cannot anticipate the precise direction of future technological change, it is important to recognize that there are numerous possible margins for innovation and productivity increases.

ORGANIZATION OF RESEARCH

The previous section described some potential avenues for technological responses to climate change adaptation in agriculture. Some of these approaches are currently under development; others are still at the frontiers of applied science. But a fundamental question is *who* will carry out the research needed for these technological advances. Many of the countries most affected by climate change have relatively weak agricultural research systems. Will the 'innovation systems' currently in place create incentives for the development and diffusion of the technologies that can mitigate the impacts of climate change on agriculture?

These questions depend on our understanding of the process of technological change in agriculture. Past experience teaches us that certain kinds of agricultural technologies are highly location-specific, while others can diffuse readily across space. Private sector firms have succeeded brilliantly in some areas of agricultural innovation; other types of innovation remain entirely dependent on public sector research.

The global research system currently invests about US\$40 billion annually in the development of new science and technology, a rate that has been sufficient to drive steady productivity growth in world agriculture over the past half century. It is certainly within the capacity of this research system to generate solutions to the problems posed by climate change. But, as this chapter will argue, the current allocation of research resources is uneven. Some countries and regions, and certain categories of research problems, are likely to attract less investment than others. There are likely to be important gaps in agricultural technologies for climate adaptation. In particular, poor countries in the tropics will struggle to find usable technologies. Moreover, some staple food crops, particularly tropical food staples, will receive little research investment from the private sector, so that public sector research will need to fill these gaps.

In this section, we explore these arguments in greater detail. This section draws heavily on recent literature on the structure and organization of the international agricultural research system, including research particularly by Alston et al. (1998); Alston et al. (1999); Pardey and Beintema (2001); Pardey et al. (2006); Beintema and Stads (2008); and related empirical work.

Location Specificity and its Implications

Some of the earliest economic research on agricultural innovation, Griliches's work (1957) on the diffusion of hybrid corn in the USA, emphasized the need for location-specific adaptation of crop germplasm. Hybrid varieties that performed well in Iowa or Illinois proved poorly adapted to conditions in Georgia and Alabama. Griliches's work emphasized the location specificity of production characteristics; however, subsequent work has pointed out that consumption attributes can also have important location-specific dimensions, particularly where crops are consumed within the households or villages where they are grown. In such cases, specific taste or cooking characteristics may have high shadow values (e.g. Bellon et al., 1998; Meng et al., 1998; Smale et al., 2001). This implies that research must focus on adaptation as well as innovation.

In the area of crop genetic improvement, plant breeders today often speak of varietal 'platforms' that embody new technological attributes. The expectation is that these 'platform technologies' will then be modified to local conditions. To use a historical example, the Green Revolution in rice was heavily dependent on the breeding of short (semi-dwarf) varieties with stiff stalks that responded well to fertilizer and devoted relatively more photosynthetic energy to grain production, and relatively less to the production of stalk and stover, than did traditional varieties. The initial semi-dwarf rice varieties were developed rapidly in the early 1960s based on known technologies, and they diffused quickly to certain production environments. But as Evenson and Gollin (2003) argued, the longer history of the Green Revolution was a story in which this basic technological platform was modified to adapt it to multiple production environments. Literally hundreds of semi-dwarf rice varieties have been released by national and international research entities, with adaptive breeding and careful selection to identify semi-dwarfs that are productive in a huge range of agro-ecological conditions. Varieties have been developed with bundles of attributes to fit many different production environments, including resistance to disease and pest biotypes that are highly localized, or to soil and climate conditions that vary widely.

As noted above, location-specific technologies are most needed for crops and production systems where environmental modification is impractical or uneconomical. For example, the basic technology package for intensive poultry production does not vary much across countries, although feed ingredients may be changed in response to local availability of materials. This reflects the fact that in modern poultry production, it is possible to control the production environment very closely. By contrast, grain farming is almost everywhere carried out with very little environmental control other than irrigation.

This in turn has important implications for developing countries, where large numbers of people earn their livelihoods from farming, and where smallholder agriculture is overwhelmingly dominated by the production of starch staple foods with minimal control of production environments. The research effort needed for climate change adaptation in agriculture will include both new platform technologies and a vast amount of adaptive research to bring these technologies to farmers, especially in the production of staple food crops for the developing world.

To make the point bluntly, effective climate change adaptation is unlikely to be achieved by having countries simply 'borrow' agricultural technologies from their

warmer and drier neighbors. Like borrowed clothing, these technologies are likely to require alterations and modifications before they work effectively. Adaptive research will be critical. Large-scale testing of available crop varieties and management systems will be essential. Some of this research can be carried out by farmers themselves, through trial and error and diffusion of knowledge (as in Bandera and Rasul, 2006, or Conley and Udry, 2010); some can be undertaken by non-governmental organizations (NGOs).

Rich countries and cutting-edge research organizations may find it valuable to introduce and experiment with new platform technologies. But in many cases, and for most poor countries, the challenge will be to build off available platforms and to construct useful technologies that can benefit farmers.

This in turn raises a number of questions about the organization of the research effort that will be needed to deliver new technologies.

Public and Private Research

Economic theory typically recognizes technological innovation as a public good. New technologies create surplus for society, but not all of the benefits accrue to those who develop the technologies. Indeed, most of the benefits accrue to producers and consumers in the form of lower costs and lower prices (e.g. Alston et al., 2009). As a result, the market tends to provide inefficiently low levels of investment in new technologies. For centuries, governments have tried to overcome this problem by offering incentives to private actors, such as patents and other forms of intellectual property rights, to encourage the development of new technologies. In addition, governments may provide direct funding for research.

In most sectors, however, private efforts dominate the market for research and technological development. In the USA as a whole, the private sector accounts for over two-thirds of investments in R&D, with universities and government supplying the remainder. However, these proportions do not apply in agriculture for reasons that stem largely from the biological properties of much agricultural innovation. In agriculture, the public sector provides about half the research investment in high-income countries. In poor countries, public sector investment accounts for the vast majority of total agricultural R&D.

Private sector research in agriculture faces a number of unique challenges, particularly for new seed varieties and other crop genetic technologies. Chief among these is the fact that by their nature, genetic materials can reproduce themselves. For most crops, farmers can save seeds from one year to the next; for animals, farmers can easily breed a high-productivity animal to pass on its genetics. The output of agriculture, in many cases, embodies the technology. From a single grain of wheat, a farmer can in principle (and over a few seasons) produce enough seeds to plant her entire field.

To some extent, these characteristics make genetic technologies in agriculture similar to technologies in other industries where outputs can easily be replicated by users, such as music and software. In those industries, innovations and investments in research are typically protected either through intense enforcement of intellectual property rights (e.g. lawsuits over illegal file sharing) or through technological tricks that make duplication difficult (e.g. access codes for software). Intellectual property rights do exist for genetic technologies, ranging from (relatively soft) 'plant breeders rights' and 'plant

variety protection', to (relatively hard) patent protections. These property rights are sufficient to spur a substantial amount of private sector research in rich countries. However, it is difficult for firms to enforce intellectual property rights on varietal technologies in poor countries because of the atomization of the agricultural sector. Particularly in developing countries, there may be literally millions of farms, operating on a small scale, and essentially judgment-proof with respect to any legal action that a life science firm might pursue.

As a result, there are few incentives for private firms to invest in agricultural technologies in poor countries. The reproducibility of seeds implies that a firm that has developed a new crop variety may have difficulty in recovering the costs of its research investments. The benefits of the new technology pass to farmers and consumers, but it is relatively difficult for private firms to appropriate these benefits.

The main exceptions to this rule have come in the areas of chemical and mechanical innovation that are dominated by private firms, and in the development and dissemination of hybrid seeds that are widely used in a few crops, most notably maize. In these crops, the physical architecture of the plants makes it easy to carry out mechanical emasculation of large populations of plants (i.e. detasseling of maize plants). These emasculated plants can be used as female parents to be pollinated from other plants. Typically, this procedure is used to cross two different varieties, using one as the male line and the other as the female line. The resultant offspring are termed 'F1 hybrids'. For reasons that remain poorly understood, these F1 hybrids display *heterosis*, or 'hybrid vigor', which leads them to outperform either of their parent lines. Significantly, seeds saved from these F1 hybrids will not reproduce the hybrid vigor of their parents; instead, they will be genetically quite heterogeneous as they will represent a reshuffling of the genes from the original parent lines. As a result, farmers who want to use hybrid seeds will typically need to buy new seeds each growing season.

Even in poor countries where well-adapted hybrids are available, farmers around the world have often proved willing to pay for them. The additional profits from using hybrid seeds will often outweigh the costs of purchasing seeds. Where this market exists, private firms have historically been willing to enter the market for improved genetics. Private firms dominate the market for hybrid maize varieties around the world, and the rents earned in this market are sufficient to induce investments in research and innovation. Thus private sector firms play an active role in genetic improvement research, but this role is limited by the functioning of seed systems and by their ability to sell hybrid seeds or other seed varieties that farmers will re-purchase year after year.

As a result, in much of the world the public sector remains heavily involved in agricultural research, including the production of relatively commercial products, such as crop varieties. As of 2000, global spending on agricultural research is estimated to have totaled about US\$40 billion, of which about three-quarters was carried out in high-income countries (Beintema and Stads, 2008, p. 4). Private research was estimated to account for about 40 per cent of the total, almost all of which was in high-income countries, where public and private spending on agricultural research are more or less equal in magnitude. In developing countries the private sector plays a very limited role in agricultural research; only about 6 per cent of total agricultural science and technology investments in the developing world were carried out by private firms.³

For agricultural research to deliver the needed technologies for climate change

adaptation and mitigation, it is quite likely that current investments in research will need to be increased, particularly in those countries (most of them poor) that currently spend very little on research. Mobilizing the resources for this research will prove challenging; agricultural science is not a high priority investment for countries with many other pressing needs, and research impacts do not necessarily take place on timescales that are relevant to politicians. At present, the world's high-income countries typically spend 4–5 per cent of agricultural GDP on research; the world's low income countries spend just over 0.5 per cent of agricultural GDP on research.⁴

This suggests that the private sector, with supporting investments from the public sector, is likely to respond effectively to the challenges of climate adaptation in rich countries. The enormous resources and expertise that are available in high-income countries should be able to solve a wide array of research problems. Some types of private sector innovation will be transferable relatively easily to poor countries, such as chemical inputs that can be sold commercially.

However, without some change in the current organization of research, it is not reasonable to assume that the private sector will develop the technologies needed for climate adaptation in poor countries, nor is it realistic to imagine that research efforts undertaken in rich countries as part of their own climate change adaptation efforts will carry over to benefit developing countries. Instead, theory and empirical experience teach us that climate change adaptation will require significant efforts in agricultural research, carried out on a local scale within developing countries themselves. There are clearly economies of scale in agricultural research (e.g. Maredia and Byerlee, 2000) so that some research can be carried out on a cross-country basis at the level of agro-ecozones. And within agro-ecozones, research does not need to be done country by country; there is considerable scope for regional collaboration. But ultimately, the task of selecting new crop varieties and tailoring new management practices will fall to national or even local research stations. The remainder of this section focuses on the problems of developing countries and the challenges of integrating national and international research structures.

National and International Structures

At present, national agricultural research entities form the backbone of innovation systems in developing countries, with small amounts of research taking place in academic institutions and non-governmental organizations. International agricultural research organizations, such as those that make up the Consultative Group on International Agricultural Research (CGIAR), account for relatively small numbers in terms of global scientific personnel or expenditures. However, most of the CGIAR centers and research units are large enough to take advantage of scale economies. They also have access to personnel and tools that are near the world technological frontier. As a result, they have had a disproportionate impact.

National research systems

The world's national agricultural research systems are highly heterogeneous. In rich countries, government research institutes and university-based laboratories are carrying out frontier research, with local experiment stations offering more detailed and production-oriented solutions to the problems of agricultural science. In poor countries there is wide

diversity of national research capacity. In Brazil, China and India, government and leading universities may operate at a level comparable to anything found in rich nations; but provincial facilities may be far less well funded and staffed. In the poorest countries of Africa, Asia and Latin America, agricultural research organizations may receive little funding and may be badly understaffed with severe shortages of trained personnel. For example, Zambia in 2008 spent about US\$8 million on agricultural research, including the budgets of the main national research organization (ZARI) and all the other relevant public, university and non-profit organizations engaged in this field (Flaherty and Mwala, 2010). Private sector firms added little more, accounting for only 2 per cent of full-time equivalent research staff.⁵ For countries like Zambia, the national system will be able to offer little support to climate change adaptation.

Several dozen poor countries around the globe have agricultural research institutions that operate at a scale comparable to that of Zambia, with total expenditures of a few million dollars. Except for the smallest countries, this level of activity is scarcely sufficient to cover the full range of production systems and agro-ecological diversity that are found across a country. Many small national programs do essentially no original research, focusing instead on testing and evaluating the materials that arrive from international institutions.

Moreover, in many national programs, operations fluctuate from year to year, depending on highly variable flows of donor funding and political interest. This kind of erratic funding makes it difficult to sustain research programs that may require many years or even decades to generate payoffs; it is not uncommon for agricultural research programs to have gestation periods of 20 years or more.

International public research

In terms of international public sector research aimed to benefit the developing world, the CGIAR plays a central role. The CGIAR provides an array of global public goods in the area of agricultural science and technology. Although its budget accounted for only 1.6 per cent of global expenditures on agricultural science and technology in 2006, the CGIAR has long had a disproportionate impact in shaping the technologies available for developing countries. Large fractions of the area planted to grain and root crops around the world are under varieties that trace their ancestry to CGIAR-developed germplasm. In many cases, CGIAR varieties are used in national breeding programs to create new and locally adapted varieties, so the attribution of impacts is problematic; the CGIAR contributions blur with those of national collaborators. Moreover, the CGIAR has long played an important role in facilitating the transfer of crop and livestock germplasm across national programs, helping, for instance, with the flow of cassava varieties from Asian countries to Latin America and from Latin America to Africa.

Previous research (e.g. Evenson, 2003) has found high rates of return to CGIAR research and has also argued that CGIAR research stimulates, rather than substitutes for, developing-country research. Having access to a stock of relevant international research increases the returns to national investments in research. If the two types of research are complementary, then international public research, whether carried out by the CGIAR or by other entities, is probably underfunded to a very high degree. These programs range from collaborative arrangements involving far-flung individual researchers or labs to bilateral arrangements involving research institutions in different

parts of the world (e.g., a relationship between two universities), as well as to bilateral collaborations involving national programs (e.g. the Brazilian research organization EMBRAPA is currently engaged in research in a number of countries in Africa).

In dealing with climate change adaptation, all of these international institutions can play a crucial role. International institutions may be able to bring a level of expertise that is not found in the national programs in developing countries. They may also have a comparative advantage in problems where the research process has real economies of scale. At the other end of the partnership, national institutions often have a comparative advantage in adaptive breeding. But flows of germplasm as well as flows of research discovery can work in many directions, too. Some strong national programs in the developing world are advancing the frontiers of technology; they may be sources of innovation for the rest of the world. And even weaker national programs may be able to provide local knowledge and special expertise that have value to the rest of the world's research community.

CHALLENGES AND IMPLICATIONS

Agricultural research has enormous potential to improve productivity and solve a wide range of problems, including the technical difficulties posed by climate change. Science has the capacity to adapt crop genetics and production systems to deal with higher temperatures, lower temperatures, changes in rainfall and emergent disease and pest problems. As Evenson and Gollin (2003) argued, the Green Revolution should be understood not as a one-time change in productivity due to the introduction of new plant varieties, but instead as a reflection of a longer-term process that involved the application of modern science to the problems of agriculture in the developing world. The Green Revolution is continuing today, though possibly at a slower pace than in the past. The challenge for agricultural science over the next hundred years will be to find the funding and other necessary resources so that this process can continue in a world subject to major changes in growing conditions.

Funding Levels and Growth

At present, the world's low-income countries receive only about 10 per cent of global outlays on public sector agricultural research. The growth rate of public research expenditures has slowed since the late 1970s; at present, annual growth in real research expenditures in low- and middle-income countries is about 1.91 per cent – down from 6.36 per cent in 1976–81 and 3.02 per cent in 1981–91 (Beintema and Stads, 2008, online data appendix). More alarming, however, are the discrepancies among low- and middle-income countries. Most of the growth in expenditure has come from a handful of larger economies, such as China and India. In sub-Saharan Africa, public agricultural research expenditures actually fell in 1991–2000, in real terms, at a rate of –0.15 per cent annually (Beintema and Stads, 2008, online data appendix). There is some evidence that expenditures have picked up in the past decade, but there is no question that funding growth remains a barrier to high-quality research in many of the world's poorest and most agriculture-dependent economies.

Not only the growth rates but the levels of agricultural R&D spending are low in poor countries. For low-income economies as a group, R&D spending in 2000 was about US\$10.1 billion. Although this is a large amount in absolute terms, it equates to only 0.55 per cent of agricultural GDP. In sub-Saharan Africa, research expenditures were \$1.2 billion in 2000, 0.65 per cent of agricultural GDP. These numbers compare to a total public expenditure in high-income economies of \$13.3 billion, for an 'intensity ratio' of 2.35 per cent of agricultural GDP (Beintema and Stads, 2008, online data appendix). The expenditure per person working in agriculture varies even more widely since output per worker in agriculture is far higher in rich countries than in poor countries.

Technology Transfer to Poor Countries

Can poor countries acquire the technologies needed for climate change adaptation? The answer is not obvious. To some extent these countries may be able to make use of technologies developed in rich countries. But many poor countries are in the tropics while many rich countries occupy temperate zones; this will hamper direct transfer of agricultural technology. Poor countries may benefit more from the advances made in tropical and sub-tropical countries with advanced agricultural research systems, most notably Brazil, China and India. But again, it may be expecting too much to imagine that technologies can be transferred so easily across national borders (or, more precisely, across the boundaries of agro-ecological zones).

This implies that for poor countries, climate change adaptation through agricultural technology will require major investments in research to be carried out within those countries themselves. The private sector may lead the way in working out new technological packages for high-value commodities and for export crops (e.g. animal products from intensive systems; horticultural crops produced in greenhouses), and there may also be some spillovers from private sector technologies aimed at rich countries. For example, if private sector companies develop drought tolerant varieties of maize and soybeans for use in the USA and Europe, the germplasm 'platforms' that they use might become available for developing countries, whether by license or through entering the public domain. However, even in maize and soybeans, private sector companies are not likely to do the adaptive work necessary to make these technologies widely useful in poor countries. This will instead fall to national research systems. And for open-pollinated crops like wheat and rice where seed markets are not well developed, private companies are unlikely to develop the needed platform varieties; this is likely instead to be the task of international organizations such as the CGIAR centers.

The Benefits of Delay

Time lags in agricultural research can be long, and it is customary in chapters such as this to argue for making an early start on research problems that may take many years to solve. The logic for this is clear, but it is worth noting that a counter-argument may also be valid. For some of the research problems facing the world, in an era of climate change, the solutions will depend on advances in basic science. Solving the applied problems – for example, breeding drought tolerant rice varieties for Africa – may become much easier once the genetic basis for drought-tolerance has been worked out. If that

is the case, there is an argument to delay research on the applied problems and instead to pour resources at present into upstream research. Money spent for research on the applied problems today may turn out to be wasted because it is premature. Normally, it is costly to delay 'solving' a research problem that imposes production losses today, but in the case of climate change the production losses may not arrive soon. From this point of view it might make sense to use the next few decades to make advances in basic science and upstream research, with a goal of developing platform varieties that allow for climate change adaptation. At that point, it might be relatively simple and straightforward to develop locally adapted varieties and breeds that incorporate the desired changes.

CONCLUSIONS

Forecasting the directions of technology over a period of decades, or even centuries, is necessarily foolish. Agricultural technology in the next 50 to 100 years will change in ways that we cannot yet predict. Advances in molecular biology and genetics, information technology, precision engineering and control systems, and many other fields of knowledge will transform agriculture in many parts of the globe, even as technological progress has changed farming in parts of the world already. Rich countries with well-organized and highly funded research systems will surely find ways of adapting to climate change through technological innovation and investments in environmental control. Some poor countries will also manage to mitigate the effects of climate change on agriculture.

In the world's poorest countries, however, the challenge will be how to cope with climate change in farming systems that are relatively untouched by new technologies. In parts of Africa and Asia today, farming has changed little in the past century. These areas already lag far behind the world's leaders in agricultural productivity. Farmers manage production shocks through diversification and mutual insurance, much as they did a century ago. If these regions cannot be drawn more effectively into the global innovation system, then 50 years from now they will lag behind even further, and they will have few resources or options with which to adapt to climate change.

Economic development will tend to draw people away from these neglected regions through migration and urbanization. In the long run, this must surely be a response to climate change as well; rural households in areas affected drastically by climate change will presumably seek other options and other locations. But this process may be slow. Migration appears to be difficult and costly for poor people. Technological advances can perhaps ease the pressure on these regions, and the requisite technologies will most likely come from the international public sector. For the development of these technologies, the international system will likely require substantial increases in funding (Alston et al., 2009). Initial efforts may focus on upstream research and the development of platform technologies. Subsequent research will involve adaptation of these platforms to local conditions. Through a concerted effort, it should be possible to reduce the impacts of climate change on agricultural productivity, even in the world's poorest areas.

ACKNOWLEDGMENTS

This chapter was written while I was on leave at the Yale School of Forestry and Environmental Studies. I gratefully acknowledge the support of that institution. I also appreciate the support of my home institution, Williams College. My views on this subject have been informed by long-term collaborations with Bob Evenson, whose retirement represents a great loss to the profession. I also acknowledge with gratitude the comments of an anonymous referee, who raised several important comments that have improved the chapter.

NOTES

1. A good – though now somewhat dated – summary of the challenges of breeding rice for drought tolerance is found in O'Toole (2004). Many recent scientific results are posted at the website www.plantstress.com.
2. This is one of the common narratives about Green Revolution HYVs. It is worth noting, however, that there is little clear evidence that the HYVs were in fact subject to higher yield variance than the traditional varieties. In some cases, the data seem to suggest that HYVs increased yield while actually reducing the absolute variance.
3. The distribution of agricultural research expenditures across developing countries is also highly skewed. China, India and Brazil together account for almost one half of the public spending on agricultural science and technology in the developing world.
4. The agriculture share of GDP is higher, of course, in poor countries, so this measure tends to overstate the differences in research spending between high- and low-income countries. Nevertheless, it is a useful way to think about the magnitude of the research challenges that are involved. A country with 40 per cent of its GDP in agriculture faces proportionally bigger research challenges from climate change than does one with only 2 per cent of its GDP in agriculture.
5. Expenditures are measured in US\$ at 2005 PPP exchange rates.

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18 Adaptation to climate change in mixed crop–livestock farming systems in developing countries

Philip K. Thornton, Mario Herrero and Peter G. Jones

INTRODUCTION

Mixed crop–livestock systems play a critical role globally, particularly in developing countries. Many of the one billion people who live on less than \$1 a day are currently fed by hundreds of millions of smallholder farmers in the tropics. In many developing countries in the future, mixed crop–livestock systems could be crucial for future food security, as two-thirds of the global population already live in these systems and a large proportion of future population growth is projected to occur within them (Herrero et al., 2009). Despite their current and future importance, the likely impacts of global change on mixed systems in developing countries have not been extensively studied to date.

In this chapter the nature and importance of mixed systems are discussed, combined with an outline of some of the key interactions between crops and livestock. Mixed systems have been seen as one stage in the evolution of agricultural systems from extensive to intensive, and this framework is briefly presented. The following section contains a short review of what we know about the impacts of climate change on mixed crop–livestock systems in developing countries and how shifts in climate and climatic variability may add to the burden faced by such countries that are largely dependent on agriculture for economic development. We then discuss adaptation and mitigation options in relation to the mixed systems that are often linked in these systems. Some examples are presented, primarily at the household level, and the chapter concludes by considering some research and information gaps and needs.

NATURE AND IMPORTANCE OF THE MIXED SYSTEM

Mixed farming systems in which both crops and livestock (both ruminants and non-ruminants) are integrated on the same farm are the backbone of smallholder production in the developing countries of the tropics (Thomas, 2007). Crop–livestock systems cover some 2.5 billion hectares of land globally, of which 1.1 billion hectares are rainfed arable lands, 0.2 billion hectares are irrigated croplands and 1.2 billion hectares are grasslands (de Haan et al., 1997). Globally they are the largest category of livestock system and in developing countries in the tropics, most ruminant livestock are associated with these systems. Although non-ruminants are found in mixed farming systems, they are usually less important than ruminants and smallholder production is often characterized by low levels of input with concomitantly low levels of output (Thomas, 2007). Crop–livestock systems produce about 92 per cent of the world's milk supply, all of the buffalo meat and some 70 per cent of small ruminant meat. About half of the total milk and meat produced

Table 18.1 Mixed crop–livestock systems in the Seré and Steinfeld (1996) classification with some examples

Code	System Category	Examples
MRA	Rainfed mixed crop–livestock systems, arid–semi-arid	• Dryland farming–sheep systems in West Asia, North Africa and India • Small ruminant–cassava systems in NE Brazil • Mixed crop–livestock farms in Burkina Faso, Nigeria
MRH	Rainfed mixed crop–livestock systems, humid–sub-humid	• Areas of S. America where rainforests are being cleared • Large areas of sub-Saharan Africa (tsetse belt)
MRT	Rainfed mixed crop–livestock systems, tropical highland/temperate	• Smallholders in Ethiopian highlands with oxen for traction • Mixed crop–livestock smallholders in highlands of Central and South America • Small-scale peri-urban dairy in E. African highlands
MIA	Irrigated mixed crop–livestock systems, arid–semi-arid	• Small-scale buffalo milk production, Pakistan and India • Animal-traction-based cash crop production in Egypt • Intensive dairy systems in California, Israel, Mexico
MIH	Irrigated mixed crop–livestock systems, humid–sub-humid	• Irrigated rice–buffalo systems: Philippines, Vietnam, India • Irrigated rice, pig and poultry enterprises in Asia
MIT	Irrigated mixed crop–livestock systems, tropical highland/temperate	• Mediterranean region • Far East Asian irrigated rice/dairy farms

Notes:

Mixed systems: in which >10% of the dry matter fed to animals comes from crop by-products or stubble, or >10% of the total value of production comes from non-livestock farming activities. These may be:

- rainfed, in which >90% of the value of non-livestock farm production comes from rainfed land use;
- irrigated, in which >10% of the value of non-livestock farm production comes from irrigated land use.

Arid–semi-arid, length of growing period (LGP) < 180 days.

Humid–sub-humid, LGP > 180 days.

Temperate regions: areas with ≥ 1 month with monthly mean temperature, corrected to sea level, >5 °C.

Tropical highlands: areas with a daily mean temperature of 5–20 °C during the growing period.

in these systems comes from the developing countries (Herrero et al., 2009). Crop–livestock systems may be relatively benign from an environmental perspective because they are typically integrated: the waste products (crop residues) of one enterprise (crop production) can be used by another enterprise (animal production) which returns its own waste (manure) back to the first enterprise (Thomas, 2007), even though manure is not enough for guaranteeing crop nutrient needs (Liu et al., 2010). Environmental problems may occur in the systems only when the intensity of production increases (de Haan, 1997; Staal et al., 2000). Crop–livestock systems are widespread in all agro-ecological zones in developing countries from the lowlands to the highlands, and they occur under widely disparate climatic and soil conditions. Some examples are shown in Table 18.1.

Mixed crop–livestock systems are particularly important for livelihoods and food security. As noted above, in addition to these systems producing close to 50 per cent of the world's cereals, they provide most of the staples consumed by poor people: 41 per cent of maize production, 86 per cent of rice production, 66 per cent of sorghum production, 74 per cent of millet production as well as 75 per cent of the milk and 60 per cent of the meat (Herrero et al., 2009; 2010). The mixed systems employ many millions of people on farms in formal and informal markets, processing plants and other parts of what are often long value chains.

The integration of crops and livestock referred to above can be achieved in different ways (see Figure 18.1 – see p. 260). In some systems livestock provide draft power to cultivate the land, and in many, they provide manure to fertilize the soil. Crop residues are a critical source of livestock feed in many mixed systems and income from livestock is often used to buffer the impacts of low crop yields in drought years. The synergies between crop and livestock enterprises offer many opportunities for sustainably increasing production by raising productivity and increasing resource use efficiency (Royal Society, 2009; Herrero et al., 2010).

The nature of the interactions between crops and livestock can also be seen in relation to general concepts of agricultural intensification. These concepts usually see increasing human population pressure on relatively fixed land resources as the driving force that leads to an evolutionary process of agricultural intensification as populations increase with time (Boserup, 1965). Intensification can take place not only at the farm level; it may also play out and be driven by decision makers at community and broader levels. There may be exchanges and market-mediated interactions between different producers who may be widely separated geographically. Examples of this 'area-wide integration' are common in parts of South Asia, for example, where manure and crop residues for animal feed may be transported many hundreds of kilometres (Baltenweck et al., 2003). The intensification process can be viewed (see McIntire et al., 1992, for example) as follows. At low human population densities production systems are extensive, with high availability of land and few direct crop–livestock interactions. As population densities increase, the level and types of crop–livestock interactions also increase through increases in demand for crop and livestock products that in turn increases the value of manure and feed resources, for example, leading to increases in both crop and livestock productivity. The final stages of intensification see a movement towards specialization in production (and thus reduced crop–livestock interaction) as relative values of land, labor and capital continue to change: fertilizer replaces manure, tractors replace draft animals and concentrate feeds replace crop residues, for example (Baltenweck et al. 2003). While there is considerable observational and theoretical support for the basic hypothesis of Boserup, there are various other factors beside population growth that are now understood to modify the intensification process. For example, environmental characteristics play a significant role in determining the nature and evolution of crop–livestock systems, as do factors such as economic opportunities, cultural preferences, climatic events, lack of capital to purchase animals and labor bottlenecks at key periods of the year that may prevent farmers from adopting technologies such as draft power (Baltenweck et al., 2003).

HOW MAY CLIMATE CHANGE AFFECT MIXED SYSTEMS IN DEVELOPING COUNTRIES?

The potential impacts of climate change on agricultural production in different parts of the world have been assessed in numerous studies (IPCC, 2007). Ranges for major crops depend on the region under study, the methods and models used as well as the emission scenarios simulated, but for maize in sub-Saharan Africa, for example, there is some consensus that yields may be reduced overall by 10–30 per cent to the middle of the century (Challinor et al., 2007; Lobell et al., 2008). Despite the uncertainties inherent in such estimates, agricultural productivity in the tropics will be severely affected by climate change in the coming decades. The losses estimated in the literature are substantially incomplete, however, in several ways. First, they are often aggregated over large areas such as the country or region, hiding great heterogeneity. For example, there will be areas in Latin America and sub-Saharan Africa, particularly in the lowlands, where crop yield reductions of 40 per cent or more may occur for the staples maize and beans, largely as a result of rising temperatures (Jones and Thornton, 2003; Thornton et al., 2009a). Second, it is not altogether clear how the impacts of carbon fertilization on crop yields in a developing-country context might best be addressed. There is ongoing debate about the size of the effects on the physiology of crops (Ainsworth et al., 2008). There are also knowledge gaps concerning the impacts of changing ozone concentrations on crop growth and how these may interact with carbon dioxide effects and with other biotic and abiotic stresses (Challinor et al., 2009). Furthermore, the carbon fertilization impacts on the low-input subsistence production systems that prevail in many developing countries will generally be smaller than those seen in controlled, high-input environments. Third, while evidence for the already-occurring impacts of climate change on crops and their associated pests and pathogens is starting to be documented, the interactions between crops, pests and pathogens are complex and poorly understood in this context (Gregory et al., 2009). Most estimates of crop productivity impacts in the face of climate change do not consider the possible effects of weeds, pests and pathogens. Fourth, agricultural production will be affected by climate change not only over the long term but also over the short; the impacts of changing extremes and increasing weather variability on agricultural production are largely unknown, pending the generation of robust estimates of future variability associated with specific greenhouse gas emission scenarios.

These issues also apply to the livestock component of mixed systems (some of the main impacts of climate change are shown in Table 18.2). The heterogeneity in crop response to a changing climate will lead to changes in the quantity and quality of crop residues. Crop residues are a key dry-season feed resource for ruminants in mixed crop–livestock systems and comprise between 45 and 60 per cent of the diets of ruminants in these systems (Blummel et al., 2006). In some conditions, while crop failures may result in no grain, there may still be substantial amounts of stover standing; stover production may not be as affected as grain yield in these cases, depending on the timing of the onset of drought. Reductions in quality and/or quantity may have serious implications for smallholder livestock keepers. Currently there is only limited information on possible climate change impacts on stover production. Total maize stover production and cattle numbers are projected to increase in all countries of East Africa to 2050, although the harvest index (percentage of total above-ground biomass that is grain) is projected to

Table 18.2 The main impacts of climate change on mixed crop–livestock production systems in developing countries

	On crops and land-based livestock	On non-grazing livestock
Direct impacts	● Extreme weather events ● Drought and floods ● Productivity losses in crops and animals (physiological stress) due to temperature increase ● Water availability	● Water availability ● Extreme weather events
Indirect impacts	● Grain quantity and quality ● Fodder quantity and quality ● Host–pathogen interactions ● Disease epidemics	● Increased resource price, e.g. feed and energy ● Disease epidemics ● Increased cost of animal housing, e.g. cooling systems

Source: Adapted from Thornton and Gerber (2010).

decrease overall, resulting in a moderate projected decrease in the availability of maize stover per head of cattle to 2050 compared with 2000 (Thornton et al., 2010). The possible impacts of climate change on stover quality are not yet clear. At the same time changes in temperature, rainfall regime and CO₂ levels will affect grassland productivity and species composition and dynamics, resulting in changes in animal diets and possibly reduced nutrient availability for animals. In many situations modifications in grazing systems management may be needed if livestock keepers are to meet production objectives (Thornton et al., 2009b).

As for crops, climate change will have significant impacts on the emergence, spread and distribution of livestock diseases through various pathways such as higher temperatures affecting the rate of development of pathogens or parasites, shifts in disease distribution that may affect susceptible animal populations, and effects on the distribution and abundance of disease vectors (Baylis and Githeko, 2006). Disease risks may change for a wide variety of reasons in addition to a changing climate, and there are many unknowns concerning the future status of existing livestock diseases and the emergence of new ones.

The impacts of short-term weather variability such as drought on livestock keepers have been widely documented: highly variable climate with frequent droughts can decimate herds and displace pastoralists (Le Houérou et al., 1988). Increasing climatic variability is likely to have substantial impacts on food and environmental security for livestock keepers in both pastoral and mixed systems, but as for crops, the nature of changing extremes and increased weather variability and their impacts on livestock productivity and household food security are essentially unknown as yet.

There are various gaps in our current understanding of what the impacts of climate change may be on mixed systems in developing countries; some of these are shown in Table 18.3 from the review of Thornton et al. (2009b), particularly related to the interactions and tradeoffs between different household enterprises and how these may play out in relation to food security and incomes, for instance. At the same time, the issues surrounding climate change and the mixed systems in developing countries need to be

Table 18.3 Some of the knowledge gaps of climate change impacts on mixed crop–livestock systems and livelihoods in the tropics and subtropics

Area	Gap
Feeds: quantity and quality	• Grazing land primary productivity impacts, species distribution and change due to CO₂ and other competitive factors • Crops: localized impacts on primary productivity, harvest indexes and stover production.
Water	• Surface and groundwater supply, and impacts on livestock • Effective ways to increase livestock water productivity
Diseases and disease vectors	• How may the prevalence and intensity of key epizootic livestock diseases change in the future? • How may climate change affect livestock diseases as systems intensify?
Biodiversity	• ‘Ecological biodiversity’: what will happen to numbers of species as systems change? • Can the plant and animal genetic resources that might be useful in the future be specified (and then conserved)?
Production systems	• Localized impacts on livelihoods • How will the mixed systems evolve in future? • Magnitude and effects of systems changes on ecosystems goods and services.
Indirect impacts	• How do human health impacts of climate change intertwine with livelihood systems and vulnerability?

Source: Adapted from Thornton et al. (2009b).

seen within the broader contexts of both global change and a changing policy environment. Regarding the former, human populations continue to increase and urbanization continues apace, and the challenges for development and food security are already considerable. Climate change and increasing climatic variability can only add to these. The policy environment within which smallholders operate is likely to change substantially in the future in response to many drivers. These include the following: the need to move to more intensive, lower-carbon agricultural systems; the increasing competition for increasingly scarce resources such as water and land; the tradeoffs required between agricultural production for human food, animal feed and biofuels; and the involvement of smallholders in international carbon markets once solutions have been found for the associated institutional issues (Rosegrant et al., 2009). Such shifts in the future may have enormous impacts on smallholder farming systems and better understanding of likely impacts at the household level will be a big step in identifying the synergies between agriculture-related climate change policies and food security, energy security and improvement of environmental quality that can help farmers adapt in the future.

HOW MIGHT HOUSEHOLDS DEAL WITH CLIMATE CHANGE?

The global community is attempting to reduce the emissions of greenhouse gases to work towards some sort of stabilization of CO₂ concentration at a global level based on effective climate policies and considerable reductions in greenhouse gas emissions.

Many alternatives exist that can reduce the emission of greenhouse gases (mitigation). In the meantime, the lags that exist in the earth system mean that some climate change impacts will be inevitable in the coming decades even if all emissions cease completely. Particularly for those who are vulnerable, options are needed if households are to increase food security, incomes and system resilience (adaptation). Below, we first consider adaptation options at the household level, and then mitigation options. In practice, the distinction between adaptation and mitigation options for smallholders in tropical systems often becomes blurred, and there are many options that serve both purposes at the same time. For this reason, at the end of this section we introduce a different typology of household responses and give some examples of each.

The Fourth Assessment Report of the IPCC (2007) reviews a wide array of adaptation options; these may be technological, such as the use of more drought-tolerant crops; behavioral, such as changes in dietary choice; managerial, such as implementing different farm management practices; and policy-related, such as market and infrastructure development. Adaptation to climate change is often framed within the context of risk management, so helping farmers understand and deal with current levels of climate variability can provide one entry point to the problems posed by increasing variability in the future and to the options that may be needed to deal with it. Longer-term approaches to adaptation are also needed; however, there may be a long lead time for the development of appropriate technology such as drought-tolerant crop varieties, for example. In addition, significant investments may be needed, particularly in the mixed extensive systems, in areas such as post-harvest food storage systems, water harvesting infrastructure and road and market infrastructure, for instance.

In the mixed systems, new opportunities are arising for households to mitigate emissions and adapt to climate change at the same time. Emissions can be reduced by managing livestock to make more efficient use of feeds, for example, which may reduce methane emissions. Management practices that increase the photosynthetic input of carbon and/or slow the return of stored carbon to CO₂ via respiration, fire or erosion will increase carbon reserves and thus sequester carbon. In the more intensive systems, various technical options related to manure management (pig, dairy and feedlots) and enteric fermentation (dairy and feedlots) can reduce emissions. (Steinfeld et al., 2006 and Smith et al., 2007 provide extensive reviews.) Payments to livestock keepers and others for environmental services, including carbon sequestration, have considerable potential for widespread application. These opportunities are not without their challenges but they represent major opportunities for diversification and increased income for households in the mixed systems (see following section).

Adaptation options have been classified in several ways, such as the level at which each option operates and the pathway taken (e.g. Kurukulasuriya and Rosenthal, 2003) and the time horizon that is being considered (Washington et al., 2006). Here we take a slightly different approach. Dixon et al. (2001) identify five main farm household strategies to improve livelihoods: intensification of existing patterns of production; diversification of production and processing; expansion of farm or herd size; increased off-farm income (agricultural or non-agricultural); and exit from farming. As Dixon et al. (2001) note, these strategies are not necessarily mutually exclusive and several of them are quite closely related. For our purposes here, we see exit from farming as an extreme form of diversification – it is certainly one possible adaptation option. Similarly, increasing off-

farm income from whatever source can be seen as a form of diversification. Expansion of farm enterprises is an important option in some places. For example, in commercial pastoral systems in some parts of Australia, farmers are increasing their scale of operations to increase incomes and spread climatic risk (Stokes et al., 2008). For many smallholder mixed systems in the tropics, however, there are probably only limited opportunities for sustainable expansion of enterprises (Dixon et al., 2001), and here we do not consider this option further. We do consider another two options that are available to tropical smallholders: extensification of the farming system (that is, reduction in the intensity of crop and livestock production) and strategies designed with the express purpose of better risk management. As before, there are overlaps between these options (e.g. diversification may often be undertaken to reduce household-level risk). We thus consider four basic strategies in relation to adaptation and mitigation options at the household level:

1. Intensification of existing patterns of production: increased physical or financial productivity through increased inputs, better technology, improved labor productivity or better farm management, for example (Dixon et al., 2001).
2. Diversification of production and processing, including agricultural or non-agricultural off-farm income via adjustments to existing enterprises on the farm or the addition of new ones.
3. Extensification of existing or modified patterns of production: by this we mean reduced productivity, or reducing the integration between crops and livestock on the farm (a reversal of the Boserupian process outlined above).
4. Better risk management: options designed expressly to address production and/or financial risk, for instance through using climatic or market-related information to help make crop and livestock management decisions.

This categorization enables options (adaptation, mitigation or options that address both adaptation and mitigation) to be viewed in terms of the impacts they may have on household income and on the variability of this income (illustrated in Figure 18.2 – see p. 261). In general terms, intensification may be expected to increase mean or expected income; the variability of income may increase, decrease or stay the same, although if it increases too much then household (economic) utility will decline. (Economic utility is an abstract measure of the relative satisfaction that the household obtains from specified levels of income.) Diversification may increase mean income and reduce income variability. Extensification may reduce both mean income and its variability, and risk management options should reduce income variability while having only limited impact on mean income. In the next section, some examples are given of each of these types of strategy at the household level in relation to adaptation to and mitigation of climate change.

SOME EXAMPLES

Intensification of Production

The impacts of climate change may not be negative in all parts of the tropics. In some highland regions of Latin America and Africa, for example, growing seasons may

actually expand as temperatures increase and low-temperature constraints to crop growth are relaxed (Jones and Thornton, 2003). Even in places where crop suitability may decrease, changes in agricultural inputs and the way farmers use them may be able to more than offset projected yield declines; the use of irrigation water and higher-temperature-tolerant crop varieties are simple examples. Intensifying production in the mixed systems may have impacts not only on household income but also on the environment. Planting trees may have a large impact on the rate of carbon sequestration in tropical systems depending on the system and region (Albrecht and Kandji, 2003). At the same time, the leaves of some tree species can significantly improve the diets of ruminant livestock because of their relatively high nutritive value and digestibility. A ruminant diet that is higher in quality will reduce the methane output per unit of product; this means that target quantities of animal product can be obtained for lower overall methane emissions and usually with fewer animals. An example is provided in Thornton and Herrero (2010) for *Leucaena leucocephala*, a tree that is widely grown in the tropics particularly for livestock fodder. To illustrate the effects of intensification of the diet, we used RUMINANT, a dynamic model for predicting feed intake, nutrient supply and methane production in ruminants that has been validated with a wide range of tropical and temperate diets (Herrero et al., 2002). RUMINANT also estimates the impact of diets on milk and meat production. Results are shown in Table 18.4 for two diets: a baseline, low-quality diet and a modified diet that included 1 kg per animal per day of *Leucaena* leaves as a supplementary feed for cattle in the dry season. As Table 18.4 shows, the baseline diet was sufficient to provide a milk yield of 1.3 kg per animal per day and a liveweight gain of 0.07 kg per day – such yield levels are not untypical of smallholder production systems in parts of Western Kenya, for example (Waithaka et al., 2006). The intensified diet increased milk and meat yield substantially, with only a moderate increase in the production of methane per animal per year. This translates into marked differences in methane production per tonne of milk and meat. It should be noted that the increased milk and meat yields in Table 18.4 are still far below what is possible, even under smallholder conditions in the tropics with local cattle breeds (Waithaka et al., 2006).

There are two key implications of these results. First, planting suitable agroforestry species on a mixed farm and feeding the leaves as a dry-season supplement can increase productivity per animal considerably, with important impacts on income (Franzel et al., 2003). In addition, the use of agroforestry trees results in increased carbon sequestration per ha, on the order of 38 tC per ha or more (Albrecht and Kandji, 2003), representing a substantial potential addition to household income even at current carbon prices (€12 per tCO₂e). Second, widespread adoption of this agroforestry option in the mixed rainfed humid/subhumid and tropical highland (MRH, MRT; Table 18.1) systems in the tropics could have substantial mitigation potential because the intensified diet would substantially reduce the number of ruminants needed to satisfy the future demand for milk and meat. Thornton and Herrero (2010) estimate that demand for milk in 2030 in the MRH and MRT systems in the tropics of Latin America, Africa and Asia could be satisfied by 245 million bovines on this intensified diet, compared with the 288 million bovines needed on the baseline diet, at a plausible adoption rate of 1 per cent per year (Kiptot et al., 2007). Meat demand could be met from even fewer (235 million).

The use of agroforestry species such as *Leucaena* as a feed supplement thus has several

Table 18.4 Impacts of diet intensification in large ruminants in the mixed systems: diet supplementation with *Leucaena* leaves

Diet	Milk yield (kg per animal per day)	Liveweight gain of growing animals (kg per day)	Methane produced (kg per animal per year)	Methane produced (kg per t of milk)	Methane produced (kg per t of meat)
Baseline: • Grazing (1.3 kg DM) • Stover, 45% digestibility (2 kg DM) • Cut-and-carry (1 kg DM) • Grain concentrates (0.5 kg DM).	1.3	0.07	27.5	58	1958
Intensified: • Grazing (1.3 kg DM) • Stover, 45% digestibility (1.5 kg DM) • Cut-and-carry (1 kg DM) • <i>Leucaena</i> leaves (1 kg DM)	3.6	0.34	35.6	25	523

Notes:

Offtake rate in beef systems: 13%.

Dressing percentage: 55% for males and females.

Proportion of animals in dual-purpose systems (i.e. producing both meat and milk): 17%.

DM = dry matter.

Source: Thornton and Herrero (2010).

impacts: it can increase household income directly via production and productivity increase; it could potentially increase household income even further via payments for the extra carbon sequestered; and the aggregated effects of widespread adoption have substantial methane mitigation potential. The simple analysis outlined above could usefully be expanded so that the impacts of adopting agroforestry species in mixed systems could be assessed in relation to possible income variability and resource use at the household level, particularly labor. The benefits of agroforestry options have been demonstrated on household food security in various situations (Jama et al., 2006), but more comprehensive household-level modeling may be needed to assess the tradeoffs that may exist in particular situations.

Diversification

In situations in which climate change impacts may negatively affect crop and livestock production, one way in which smallholders can adapt is to seek additional ways of generating household income. This income may be generated through on-farm or off-farm activities. An example of the benefits of diversification based on modeling studies comes

from the extensive mixed (agropastoral) systems in southern Kenya that are undergoing rapid socioeconomic change, and in which households are highly vulnerable to climate change (Thornton and Herrero, 2009). Kajiado district in southern Kenya is mostly semi-arid bush and grassland with swamps in the southern part that provide critical short-term grazing for animals and water for pastoralists, and also support irrigated agriculture. The district is characterized by variable rainfall within and between years, and droughts are frequent. Historically, the resident Maasai have coped with this variability by moving their livestock over large areas of land to access adequate forage and water resources. Many households are poor and in southern Kajiado over 50 per cent of the population is living below the poverty line (Boone et al., 2005). The population of Kajiado district has more than doubled since 1979 while the livestock population has remained relatively constant. Many Maasai households have thus diversified into cultivation, wage labor or small-business operations, and there has been considerable expansion of cultivated areas and permanent settlements.

We have carried out integrated assessments using a detailed ecosystem model coupled with household models to weigh up different management options that balance the needs for wildlife conservation, human well-being and ecosystem sustainability (Boone et al., 2005; Thornton et al., 2007). Household objectives tend to revolve around food security issues and the importance of keeping cattle as a capital and cultural asset. In this region a process of subdivision of the group ranches is under way, involving the dissolution of group ranch titles and subdivision of the rangelands into private parcels. This process is driven in part by concerns over long-term access to resources. Modeling results indicate that subdivision usually results in substantial reductions in livestock numbers, partially because households have to sell more animals to generate the cash needed, with serious long-term consequences for herd sizes and food security. In the situations where subdivision does occur, the models suggest that households with more livelihood options, even if relatively poor, may be better able to cope. An example of these results is shown in Figure 18.3 (see p. 261), where even poor households on fragmented rangeland can partially offset the negative effects of this stressor by engaging in more livelihood options such as running a small business and growing vegetables in small irrigated patches. These activities allow households to produce more of their own calories and thus reduce their dependence on other sources of food (a partial indicator of food security). There are other viable diversification options too; for example, leasing programs are operating in parts of Kajiado district in which households are compensated directly for not erecting fences that can hinder wildlife movements in and out of protected areas that generate substantial levels of tourist revenue. These programs can substantially increase the incomes of poor households, particularly in drought years (Reid et al., 2008). It is likely that such diversification options may be able to offset the negative impacts of other stressors such as changes in climate and climatic variability, and we are currently undertaking work to evaluate this possibility.

Another example comes from the more intensive mixed systems of Vihiga district, western Kenya. Poverty rates are high here as well, even though households obtain some 65 per cent of their income from off-farm sources. The main cash crop is tea and in addition to food crops such as maize, beans and bananas, income from dairying local Zebu animals is important for many households. Using various modeling tools, Claessens et al. (2010) evaluated the possible impacts of climate change from a variety of climate

models and greenhouse gas emission scenarios to 2050 on households in Vihiga. They found that there are likely to be negative economic impacts on many households but that the addition of relatively high-yielding dual-purpose sweet potato varieties to the farming system (the roots being used for food and the vines as a livestock feed) could at least partially offset some of these negative consequences. Part of this effect comes about through increased milk production as a result of feeding sweet potato vines to lactating animals (Claessens et al., 2010). While there are many sources of uncertainty in all these modeling studies, the results do suggest that diversification of existing production patterns or addition of new off-farm activities can offset at least some of the projected impacts of climate change on households in the mixed systems.

Extensification

In addition to intensification and diversification, there are other ways in which households dependent on agriculture may have to adjust their livelihood strategies in the face of climate change. It seems very likely, however, that there are limits to the ways in which existing agricultural systems can be modified, and climate change in some places may be so great that coping ranges and buffering capacities are exceeded. In such cases, enhancing the food security and well-being of farming communities may require radical changes in livelihood strategies. It can be envisaged that hotspots may exist where changes in climate and other drivers may affect mixed farming households to such an extent that cropping may become essentially impossible, and the household's dependence on livestock and/or off-farm income may thus increase. Indeed, in some circumstances one could hypothesize a transition from a sedentary mode of production to a nomadic one. While this rather flies in the face of the usual evolution of agriculture as outlined by Boserup and others (outlined above), it probably is plausible. (Climate change may plausibly affect the Boserupian ideal of systems evolution in other ways too, particularly in situations in which productivity losses are accompanied by lack of technological innovation to help smallholders adapt.)

This possibility was investigated in the study by Jones and Thornton (2009). In some places the local effects of higher temperatures may have damaging effects on crop production, regardless of changes in rainfall amounts and regime. These places include parts of the tropics that are already marginal for crop production; as these areas become hotter and water increasingly limiting, livestock may provide one of the only alternatives to cropping. Areas in sub-Saharan Africa have been identified where such transitions might occur. For the currently cropped areas of the continent, a recent study estimated probabilities of failed seasons for current climate conditions and compared these with estimates obtained for future climate conditions in 2050 using downscaled climate model output for two contrasting greenhouse gas emission scenarios. Cropping in areas with fewer than 90 reliable crop growing days per year (an indicator of season length and reliability) becomes very risky. Using this value as a cut-off point, there are widespread parts of the continent that are currently classified as mixed crop–livestock, rainfed arid–semi-arid systems in which cropping is possible now but may well not be in 2050. These transition zones differ in their accessibility, which may have considerable impacts on the type of adaptation options that may be viable. For those that are relatively close to large human settlements, there may be options for both integration of livestock systems

Table 18.5 Characteristics of the areas in the mixed crop–livestock rainfed arid–semi-arid (MRA) system in sub-Saharan Africa in which cropping may become highly marginal by the 2050s

	Good accessibility ($< 200^1$) (Mean 123)	Poor accessibility ($> 200^1$) (Mean 584)
Area, km ²	118 246 (44 012)	607 905 (191 596)
Human population, million (2000)	11.66 (3.34)	15.36 (5.76)
Cattle population, million	2.20 (0.86)	13.55 (4.05)
Sheep population, million	3.86 (1.03)	9.54 (2.65)
Goat population	2.71 (0.75)	9.90 (3.22)
Infant mortality rate per 1000 births	81.0 (4.5)	97.5 (1.0)
Stunting rate, %	29.0 (1.3)	36.6 (0.6)
Wasting rate, %	22.3 (1.2)	29.7 (0.4)

Notes:

¹ Minutes of travel time to a town or city with a population of more than 250 000 (Nelson, 2007).

Values shown are the mean (and standard deviation) of four combinations of two climate models and a higher- and lower-emission scenario, stratified by accessibility.

Source: Adapted from Jones and Thornton (2009).

into the market economy and for off-farm employment opportunities. For transition zones that are more remote, on the other hand, both market and off-farm employment opportunities may be much more limited. Currently, significant populations of people live in these more remote transition zones and they are widely spread throughout West, East and southern Africa. These areas are characterized in Table 18.5 in terms of their area, human population, cattle, sheep and goat populations, and three poverty proxies stratified by accessibility: infant mortality rates, stunting rates (chronic undernutrition) and wasting rates (acute malnutrition). The areas of the transition zones with good accessibility are much smaller than those areas with poor accessibility, and their human population density is considerably greater. There are substantial increases in the poverty proxies for the poor accessibility transition zones (Table 18.5). Areas that are far from markets already have higher poverty rates than areas closer to markets: the results here suggest that climate change impacts in these areas are likely to affect the poor disproportionately.

At a minimum, these areas will need highly targeted schemes that promote livestock ownership and facilitate risk management where this is appropriate, as well as efforts to broaden income-generating opportunities where this is feasible. A widespread reversion to agriculture dominated by mobility would have far-reaching social, environmental, economic and political implications at local, national and even regional levels: it could increase conflicts over natural resources, accelerate the degradation of already fragile ecosystems and profoundly complicate the integration of nomadic communities into national polity, among other things (Lufafa et al., 2010). This ‘reverse genesis’ of agriculture may be a relatively extreme adaptation pathway in marginal environments, but some of the implications are currently being investigated through field surveys and modeling work in parts of East Africa. All in all, there is little doubt that the coming

decades will see substantial shifts in the patterns of cropping and livestock keeping in the more marginal parts of the tropics.

Risk Management

Climate change is expected to bring with it an increase in climatic variability (IPCC, 2007). Increased frequency of floods and droughts can have devastating impacts on agricultural (and other) systems. Although there are many unknowns with regard to the nature of the increased variability of climate in the tropics, its impacts on crops and livestock can be demonstrated quite simply (see Thornton and Herrero, 2009, for example). Floods and droughts may lead to complete destruction of crops while increased frequency of droughts may result in decreased herd sizes because of increased mortality and poorer reproductive performance, severely compromising food security. Increasingly, climatic variability is likely to have substantial impacts on environmental security as well, as conflicts over livestock assets and natural resources may well escalate in the future.

More effective risk management may be able to help many households adapt to climate change. Several examples can be given, one being the use of weather information. Hellmuth et al. (2007) describe a project that was launched 25 years ago in Mali in recognition of the fact that rural communities need help in managing the risks associated with rainfall variability. This is now an effective collaboration between government agencies, research institutions, media, extension services and farmers. Ten-day bulletins are produced by multidisciplinary working groups that provide the basis for information and advice to farmers as well as to national policy makers on the food security status of the country. They are disseminated in various ways and report on the state of crops, water resources and weather conditions as well as crop health issues, pastoral issues, animal husbandry and agricultural markets, in addition to predicting future conditions. When farmers have good climate information they are able to make better management decisions that can lead to higher yields and incomes (Hellmuth et al., 2007). Some key issues remain related to the effectiveness of climate forecasts for crop and livestock management that still need to be addressed, particularly related to the design and implementation of effective mechanisms for the delivery and utilization of this type of information (Thornton et al., 2004).

Another example is livestock insurance schemes that are weather-indexed (i.e. policy holders are paid in response to ‘trigger events’ such as abnormal rainfall or high local animal mortality rates). Insurance schemes for crops are quite widespread but there are few examples of functioning schemes for livestock, and there may well be limits to what private insurance markets can achieve for large vulnerable populations facing covariate risks linked to climate change (UNDP, 2008). A recent development in index-based livestock insurance is the potential for public–private partnerships in situations where the incentives and risks involved do not make it feasible for the private sector alone. Such an index insurance scheme based on satellite imagery is being piloted in several areas of drought-prone northern Kenya (Mude, 2009).

A third example is changing the mix of livestock species. Cattle-keeping pastoralists in parts of northern Kenya have adopted camels as part of their livelihood strategy as a result of drought, cattle raiding and epizootics. More widespread adoption of camels

and goats in the drylands is now being observed in many other places. Changes in herd composition within species can also be observed as a risk management strategy. For example, FulBe herders in the semi-arid zone of Nigeria have switched their herds from a grass-dependent breed to one that can digest browse much more easily in the face of declining feed availability (Blench and Marriage, 1999).

The future honing of risk management techniques to make adaptation more effective is likely to include a blend of the old and the new. Farmers in the tropics already have a long history of coping with climatic variability and have developed many different ways of addressing the issue (Matlon and Kristjanson, 1988). At the same time several tools and approaches are now available that can be used to develop and fine-tune climate risk management strategies that are specifically tailored to stakeholder's needs (Cooper et al., 2008) including short- and medium-term weather forecasting, and their effectiveness is likely to continue to increase in the future.

CONCLUSIONS

The mixed crop–livestock systems of the tropics are critical for the current food security of large numbers of people, many of them poor. This role is unlikely to change significantly any time soon, particularly in south Asia and sub-Saharan Africa, although there is considerable debate as to whether smallholder agriculture can really deliver sustainable development and poverty alleviation. Given the massive increases needed in agricultural and labor productivity, particularly in Africa, smallholders may essentially be marginalized (Collier and Dercon, 2009), although there have been examples of the smallholder sector delivering economic development, and given appropriate support, these could be replicated (Wiggins, 2009). The future role of smallholders in global food production and food security in the coming decades is thus a key uncertainty in the context of continued population growth and urbanization, income growth, and technological and climate change. In any case, it is clear that there are real needs for adaptation and mitigation options that can help crop–livestock farmers address the problems caused by global change.

Many options exist, but as the IPCC (2007) notes, both for mitigation and adaptation, much more needs to be done than is currently being undertaken to reduce greenhouse gas emissions and to reduce vulnerability to future climate change. Almost all mitigation and adaptation options have costs associated and there may be economic, social and institutional barriers to their uptake. In the future, incentives for mitigation (via carbon payments, for instance) are likely to lead to systems' adaptation to climate change as they imply changes in the management and repertoire of activities that smallholders may take on board. Much work remains to be done to increase our understanding of these costs and barriers, and of the most appropriate and effective mechanisms for implementing mitigation incentives, in specific situations.

There is much other work to do as well. There are key component knowledge gaps, outlined in Table 18.3, but there is also a need for much better incorporation of the issues associated with changing variability at the household level. This implies a need for comprehensive household modeling activities as well as appropriately detailed information from global and/or regional climate models.

Finally, we highlight the importance of international efforts to assemble the data and tools needed to quantify and evaluate the impacts of different adaptation and mitigation options. There are now considerable holdings of publicly available spatial and other data concerning natural resources (such as the Consortium for Spatial Information initiative of the Consultative Group for International Agricultural Research, www.cgiar-csi.org) and household surveys (such as the International Household Survey Network, www.ihnsn.org), for example. Still, there is often considerable uncertainty in basic information related to agricultural production, and while high-resolution remote sensing, sophisticated information and communications technology as well as crowdsourcing are adding to the range of what is possible, much remains to be done.

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19 Insurance as an adaptation to climate variability in agriculture

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INTRODUCTION AND SCOPE

Insurance is the largest global industry with total revenue of US\$3.2 trillion (Mills, 2005). It is also one of the most vulnerable sectors to the effects of climate change. Penetration rates in developed countries are 100 times larger (US\$2700 per capita) than in developing countries (\$25 per capita). The growth potential of the industry is therefore great but there are risks involved, especially for insurance policies offering coverage against damage caused by natural catastrophes. The industry is aware of the main challenges that climate change poses for its healthy growth and expansion (ECA, 2009). It is also a leading sector in the fight against climate change and a leading voice in requesting that security levels for construction, infrastructure and human settlements be upgraded and that exposure be reduced. Standard actuarial techniques, insurance contracting and risk transfer and pooling will not be sufficient to avoid significant losses if the insurance industry is to keep expanding and offering protection against natural catastrophes (ECA, 2009).

Although it is relatively small, the agricultural insurance sector is also expanding in many countries.¹ With almost no exceptions, growth in insured capital and coverage expansion has been coupled with intense public participation in the form of premium subsidies, public reinsurance, tax rebates, direct insurance participation and market regulatory frameworks. Many policy issues associated with the role of public agencies in agricultural insurance have been discussed in the literature for decades (Hazell et al., 1986; Cafiero et al., 2007; Bielza et al., 2008a, 2008b; Meuwissen and Huirne, 2008; Mahul and Stutley, 2010).

Many of the challenges that threaten the survival of insurance companies also affect agricultural insurance branches and companies. To the extent that agriculture will be profoundly transformed by climate change, the insurance sector will have to adapt to new risk profiles while at the same time keeps constantly innovating and seeking to offer new policies.

This chapter has three goals. We first summarize the most recent literature on insurance and climate change (CC), highlighting the major challenges involved and industrial reactions to what the sector seems to consider its major CC threats. The role of the government in offering support and assistance in the event of a catastrophe is obvious and hardly contested, but the boundary separating business and government responsibilities is under discussion and is by no means fixed. Our second goal is to summarize the main trends in agricultural insurance around the world. We describe the major approaches to insurance found in developed, emerging and developing countries. Our third goal is to

provide quantitative results from two sets of analyses. In the first, we report differences in premiums for current and future climates (IPCC A2 scenario, 2070–2100) for three cropping options and 12 sites in Spain. In the second set of results, we offer Monte Carlo simulations showing the extent to which errors in the yield distribution parameters or even density functions can affect actuarially fair premiums.

INCREASES IN DISASTERS AND CATASTROPHES: EFFECTS ON THE INSURANCE INDUSTRY

In recent decades the severity and frequency of extreme climatic events have increased significantly, causing severe damage, casualties and injuries around the world (Hazell, 2006; FAO, 2008; Giddens, 2009); see Figure 19.1 (p. 262). Most of the disasters and catastrophes have been caused by extreme hydroclimatic events, with floods, hurricanes and droughts responsible for 65 per cent of the recorded natural disasters between 1990 and 2005 (Figure 19.2 – see p. 263).

Many authors suggest that the increase in human and economic losses caused by extreme events is partly due to socioeconomic factors (Botzen et al., 2009). These include population growth, the increase in one-person homes, environmental degradation, the industrialization of the most vulnerable areas (flood plains and coastal zones), the increasing vulnerability of modern societies and increases in population density and in the concentration of economic activity (Berz, 1999; Hoff et al., 2003). Furthermore, the growth and expansion of insurance coverage and of certain behavior associated with risk-compensation phenomena has increased the number of reported losses (Vellinga et al., 2001). Most models predict that the frequency and severity of extreme events will increase during the twenty-first century (Mills, 2005; IPCC, 2007).

In predicting risk scenarios, we find that future risks associated with CC are subject to a high degree of uncertainty (Mills, 2005; Hanemann, 2010; Schiermeier, 2010). Probability and expected damage evaluations are thus subject to large prediction intervals. For instance, damage associated with storms depends more on their trajectory than on their strength. There is evidence indicating that CC is augmenting the tails of damage distribution functions (Kousky and Cooke, 2009). The distribution tails of damage increase exponentially with average temperature increases. The subsidence of clay soils, damage to buildings and infrastructure, convective storms and more intense hailstorms and tropical storms are associated with increases of average temperature (Dlugolecki, 2008).

Baethgen (2010) argues that the uncertainty involved in developing likely precipitation scenarios is greater than that associated with predicting temperature changes and much greater at the regional than at the global level. Although downscaling methods allow for better modeling runs at the regional level, climatic patterns are much more difficult to calibrate to a present-day situation: ‘these downscaled climate change scenarios can be viewed as scenarios with higher level of detail of the same (and often larger) level of uncertainty’ (Baethgen, 2010, p. 73). In addition to regional uncertainties, Schiermeier (2010) cites three other ‘real holes’ in climate science that have a direct influence on insurance and agriculture, namely, (a) precipitation projections (especially in the winter) attested to by the inability of climate models to properly reflect the extent to which precipitation has

already changed in present times or to predict mega-droughts lasting several decades that have struck parts of Africa in the past; (b) atmospheric aerosols, some of which enhance cloudiness while others reduce it, making it more difficult to predict ice formation and the severity of hailstorms; and (c) paleoclimatic data (proxies) and the inconsistencies between backward projections and climate data inferred through tree rings.

Most representations of the sectorial effects of climate change relate likely effects to various levels of temperature increases. Figure 19.3 (based on ECA, 2009) provides a very general description of global processes (see p. 263). With 650 ppm of CO₂ in 2070, there is a 94 per cent probability that the global temperature will increase by 3 °C (Stern, 2009).

Because of its dependence on climate and its significant use of land, agriculture will be especially vulnerable to any increase in natural disasters and to climate change. Although climate hazards do not heed political boundaries or discriminate by income level, developing countries are much more vulnerable to increasing risks than developed countries, with Africa perhaps the most vulnerable continent (Dinar et al., 2008; Leary et al., 2008; Collier et al., 2009).

How significant is the challenge facing the insurance industry? Giddens (2009) writes that the financial resources needed to compensate for the damages caused by a catastrophe can be 100 times larger than the revenue collected from insurance premia sold in the affected region. The insurance industry, including insurers and reinsurers alike, faces an unknown challenge in responding to the effects of climate change (Grant et al., 2007).

The principal threat facing the industry is the prospect of unanticipated changes in the nature, magnitude and location of insurable hazards (Mills, 2005). Among the climate risks with the largest influence are catastrophic events (Hecht, 2008) that endanger the financial returns of private insurers (Stephenson, 2007). In general, it is difficult to predict the likely losses associated with a single hazard because of the low probability of extreme events and the number of social factors that influence such losses (Botzen et al., 2009).

Dlugolecki (2008, p. 77) identifies five technical risks and CC challenges for the industry: (a) historical models of costs may not be useful because the scale and frequency of events may be greater than previously experienced; (b) risks may be incorrectly rated, with the probability of an extreme loss being assessed too low; (c) exposure is likely to be too high because the maximum probable loss may be underestimated and incorrect reinsurance planning may result; (d) claims-handling capacity is too low because the extent and intensity of the destruction that may be experienced in new extreme events may be beyond that which we have seen previously; and (e) credit ratings are too generous because the probability that someone's capital will be seriously depleted by a disaster is underestimated. Other authors have added several other potential challenges: changes in the absolute and relative variability of losses (Mills, 2005); increases in the occurrence of adverse selection (Hohl, 2004); and problems associated with changes in the notion of 'insurable risk', which in effect puts pressure on governments to assume risks that in the past could be insured (Hohl, 2004; López and de Paz, 2007).

Against the backdrop of this threat, other authors see increasing business opportunities (López and de Paz, 2007; Maynard, 2008; Botzen et al., 2009). A number of challenges remain ahead if the insurance industry is to avoid serious disruption and risk of bankruptcy. Under unknown or unexpected risk exposure, the insurance sector typically reacts by reducing coverage, improving loss adjustment procedures, transferring more risk (at a greater cost) and requesting that governments bear a larger share of the residual

risk (Botzen et al., 2009). The capacity of the industry to cope with the risks associated with CC depends to a great extent on its ability to transfer risks to reinsurers and other agents. The more underwritten policies can be transferred to the reinsurance market, the more and deeper the risks insurers can be underwritten (Hecht, 2008). Risk transfer is the most effective means of offering coverage for infrequent but severe events (ECA, 2009).

Mills (2009) and ECA (2009) emphasize the role of insurers as proponents of mitigation strategies. Underlying this unconventional role for the industry is the recognition that without mitigation strategies involving technical codes, carbon-free processing, training initiatives and even activities using clean development mechanisms, actuarial techniques will not reduce the risk that CC entails. Botzen et al. (2009) claim that even with adaptation and risk mitigation, natural catastrophes may represent an unbearable load for the insurance industry in The Netherlands, which necessarily implies that the government should match the industry in its involvement, at least for floods. As an adaptation mechanism, insurance is a double-edged sword; while it is an instrument used to compensate for, pool, spread and transfer risks, it nevertheless discourages mitigation strategies and increases risks exposure (Adams, 2007 is a classic study of compensation mechanisms). This explains why leading reinsurance companies highlight the need to augment mitigation strategies, increasing technical security standards in all areas vulnerable to physical damage (e.g. cities, infrastructure, levees, buildings, roads; see ECA, 2009). The message is clear: insurance can provide compensation to the victims of catastrophes, but it reduces the incentive for self-protection and discourages efforts to lower exposure. Public policies thus play a leading role in helping the insurance industry to increase penetration rates, underwrite more policies and simultaneously raise mitigation standards and incentivize reductions in risk exposure.

With regard to CC, the fundamentals of the insurance industry may be under question because of the divergent approaches used. As Mills (2005) writes,

Disjointed modeling traditions and inconclusive attribution analyses hamper the industry's ability to assess weather-related risks and regulators' ability to safeguard both insurers and consumers. Insurers' weather related loss models focus primarily on catastrophic events (to the exclusion of a broader array of small-scale events that have larger aggregate impacts), are predicated on extrapolating historical trends and largely neglect life and health impacts. In contrast, the climate change community's models are future-focused, yield results not easily applied to business decision making and underestimate the physical and economic impacts of abrupt climate. (Mills, 2005, p. 1043)

AGRICULTURAL INSURANCE AS AN ADAPTATION TO CLIMATE CHANGE

Insurance is designed to provide compensation for losses that occur with relatively low frequency and whose probability is known based on past experience. Correspondingly, insurance is not suitable for use in offsetting downward trends: there would be continual indemnities and the business would no longer be viable from an actuarial perspective. For this reason insurance is not a suitable tool for fighting against global warming itself in those regions with decreasing yields. However, it has the potential to buffer the impact of increasing extreme climatic events. If their probability increases, insurance will have

to adapt its premiums and attempt to foresee such changes, but it will potentially be a useful tool in such a scenario.

Many authors grant agricultural insurance a leading role in promoting agricultural adaptation to climate change (Dolan et al., 2001; Hohl, 2004; Mcleman and Smit, 2006; Skees et al., 2008; ECA, 2009; Burgaz, 2010; Schwank et al., 2010). Even though insurance is a very useful tool for the financial management of agricultural production, it cannot be the only means of adapting to new climate conditions (Fosse and Changnon, 1993). It should be accompanied by a continuous risk assessment and the implementation of prevention and risk reduction measures (Schwank et al., 2010). Generally speaking, to cope with farm risks, farmers can reduce risk exposure through on-farm management strategies (e.g. diversification, storage, crop protection, preventive animal vaccination, use of versatile capital investments) or can reduce their vulnerability by transferring risk out of the farm (with insurance or other types of contractual or formal agreements).

In the absence of instruments that can be used to transfer or diversify risk, most farmers prefer to reduce exposure even if this requires a reduction in expected returns. In developing countries, rural households lack access to financial instruments that they can use to leverage 'good' seasons or cope with 'bad' seasons. In poor rural areas, extreme events are associated with capital disinvestment, serious business interruption and the destruction of natural assets (Hansen et al., 2007; Baethgen, 2010).

In thinking about ways to cope with CC risks in agriculture, many authors highlight the potential use of seasonal weather forecasts (Liu et al., 2006; Cabrera et al., 2007; Hansen et al., 2007). Known phenomena like El Niño–Southern Oscillation (ENSO) are useful for predicting climatic conditions before seasonal cropping decisions are made.

Agricultural insurance can contribute to agricultural adaptation to CC in the following areas (Hohl, 2004; Ward et al., 2008): farmer protection from variability in crops' price and yield; the promotion of innovative risk management instruments; cooperation with governments by means of partnerships between insurers and public agencies; information gathering and risk and hazard analysis; the use of loss adjustment techniques in case of a catastrophe (Burgaz, 2010); financial incentives for investment in relevant mitigation strategies; and last, better credit access. The project 'Horn of Africa Risk Transfer for Adaptation' (HARITA) is an example that explicitly implements index insurance as an adaptation measure. In this project, smallholder farmers from Ethiopia purchase unsubsidized index insurance as part of an adaptation package (Dinku et al., 2009; Oxfam America, 2010).

Dlugolecki (2008) defines slow-onset problems as those that CC will inevitably and gradually create, with droughts and increases in sea level as two relevant examples. In the case of droughts, micro-financing of about \$100 million will be required to provide insurance coverage for slow-onset events just to insure loans of \$50 for the poorest 200 million agricultural households in the world (ibid.).

EXPERIENCE WITH AGRICULTURAL INSURANCE

Types of Agricultural Insurance

Crop insurance is used mainly to cover harvest losses due to weather events. It includes single-risk insurance, combined insurance and yield insurance (multiple-peril crop insur-

Table 19.1 *Insured risks*

Insurance	Covered risks
Single risk (named peril)	Hail (hail + fire)
Combined risk	Hail, frost
Different for different types of insured crops	Hail, frost, flood Hail, frost, storm, flood
Yield insurance / MPCl	All climatic risks Hail, fire, frost, storm, flood, drought (plant diseases and pests usually not covered in Europe)

Source: Author's elaboration.

ance, MPCl, in the USA) according to the nature and number of the covered hazards. Table 19.1 shows the main types of insurance and their associated risks.

Single-risk insurance (especially hail insurance) has a long history and is well developed in Europe and North America. Insurance policies developed to also protect against the risk of frost or against a limited number of meteorological events can be referred to as combined-risk insurance or pluri-risk insurance. Usually, private companies provide coverage only against hail and fire or against a limited number of risks, including floods or excessive rain. As government involvement in insurance increases, more comprehensive coverage against all climatic risks may be provided by insurance (Bielza et al., 2009; Mahul and Stutley, 2010).

Systemic risks or highly correlated risks affecting large areas or a large number of insurances at the same time have long been considered non-insurable and, in fact, are difficult to insure because of the potential magnitude of the indemnities. Thus combined insurance can cover most risks affecting crops, but it does not cover the significant systemic risks that demand a very high level of reinsurance expenses and thus can usually only be covered if there is public support or public reinsurance. When insurance also covers systemic risks such as drought, it is generally called yield insurance. Comprehensive yield insurance systems are mostly found in countries where there is strong public involvement in agricultural insurance (for example, in the USA, Spain or Austria).

It is useful to clarify the particularities of yield insurance from a technical point of view. There are several types of insurance that have been classified as yield insurance, including multi-peril insurance or multi-risk insurance in Europe. The common characteristic of these types of insurance is that they protect against all main climatic hazards that can affect yield (although plant diseases and plagues are not covered in most cases). However, these types of insurance work very differently than American 'multiple-peril crop insurance' (MPCl). MPCl provides coverage against all possible natural risks that can cause a decrease in yields, including plagues, droughts and diseases. In the USA, MPCl damages are calculated simply as the difference between the guaranteed yield and the actual yield. In contrast, under the European yield insurance, it is necessary to ascertain which risk has caused the loss and to what extent. The difference is important: the European model has higher loss-adjustment costs because

the insurer must assess the loss (mostly done in the field), but it helps to avoid moral hazard, which is one of the most significant problems plaguing the US insurance system.

Revenue insurance includes price or market risk protection on top of the guarantees offered by crop insurance. In the 1990s revenue insurance was developed in the USA and income insurance in Canada. Revenue insurance programs have become popular in the USA and provide coverage when there is a decrease in the combination of price and yield.

Index insurance products have been developed in recent years and have non-negligible potential as means of adjusting to climate change. Index contracts are more like financial derivatives or options than like insurance contracts. However, under certain conditions they can be considered insurance: 'The weather derivative can be brokered as an insurance contract or as an over-the-counter traded option' (Turvey, 2001, p. 334). Weather derivatives or weather options are managed by the private sector so there is limited information available about them. Instead, there are many experiences already documented with various types of weather or index insurance (Bielza et al., 2008b, Skees et al., 2008; Hazell et al., 2010).

Some authors argue that future insurance contracts should grow as variants of index insurance to avoid the administrative costs and welfare losses associated with moral hazard and adverse selection (Skees et al., 2008; Hazell et al., 2010). In fact, the main advantages of weather insurance over traditional crop insurance are that they avoid moral hazard and adverse selection problems, thus allowing for higher levels of coverage. It is easy to sell them through banks or through any other financial organization; they are transparent and affordable and entail very low administrative costs. However, an insured event may not always reflect the production losses that individual farmers experience, so they are more appropriate for very homogeneous areas and for reinsurance.

Index insurance pricing is a complex issue: traditional methods of pricing financial derivatives have been used, but insurance or actuarial methods may be more appropriate. At the same time, the possible impact of climate change is difficult to assess.

There are many types of index insurance. We can distinguish two main groups (Bielza et al., 2008b):

- area yield and revenue insurance (the index is an area's average yield or income);
- indirect index insurance, which is exogenous and yield tailored. These forms of insurance can be based on one or several indicators:
 - meteorological indicators (the indices measure variables such as rainfall or temperature);
 - agro-meteorological indicators (the indices measure indicators including the agronomic parameters of the crop such as soil moisture or leaf area index);
 - satellite imagery indicators (using vegetation indices computed from satellite images).

Within the indirect index category we can find examples of exogenous index insurance and of yield-tailored insurance. The exogenous indexes either involve a fixed payment per unitary index decrease (e.g. a payment of €1 per 1 mm of rainfall shortfall) or are proportional (a 50 per cent decrease in rainfall will trigger compensation in the amount of 50 per cent of the insured capital). The yield-tailored examples are more complex, and

yield is adjusted by estimating a model that either combines several indicators or uses only one.

Index insurance products have actually been implemented as pilot programs all around the world (see Bielza et al., 2008b; Barnett et al., 2008; Hazell et al., 2010, for comprehensive and detailed descriptions of existing index-based risk transfer products). Index insurance can help manage catastrophic and highly covariate risks such as hurricanes, floods and severe (possibly back-to-back) droughts, serving clients such as public or NGO relief agencies that need to respond urgently in case of catastrophes. It can also be useful for financial agencies providing credit, rural households and input suppliers in areas subject to specific and easily measurable climatic hazards (Hazell et al., 2010).

Livestock is subject to sanitary risks that can change with climatic conditions (as changes in temperature and humidity can affect disease propagation), and livestock production is also dependent on forage and pasture availability which is in turn subject to climatic hazards. Thus climate change can affect livestock risk on two different fronts.

Livestock insurance has long existed in many countries for accidents and for non-contagious diseases. Epidemics and diseases that can directly affect human health are usually regulated by governments and covered by *ad hoc* aid, so there is less need for insurance to cover this type of animal disease. In some European countries insurance is also available that covers indirect losses due to diseases and epidemics (including the costs of withdrawing dead animals and of trade and animal movement restrictions); again, this insurance often depends on public support. In Europe, livestock insurance is significant in Spain, Sweden, the UK, Bulgaria and the Czech Republic (cf. Bielza et al., 2008a).

Forage and pasture insurance, because of difficulties involving loss assessment, has only been recently developed in some countries based on satellite indices. In Canada and Spain, two index insurance products have been offered since 2001 that cover forage production. Canadian Pasture Insurance was offered in the province of Alberta. It is based on a pasture vegetation index (PVI) generated from the Normalized Difference Vegetation Index (NDVI). Farmers can insure native, improved or bush pasture. In Spain, a NDVI insurance scheme was engineered mainly to protect farmers from droughts affecting pasture areas. This insurance product has been offered to all farms performing extensive livestock production, specifically with cattle, sheep, horses and goats (Bielza et al., 2008b).

Recent Trends in Agricultural Insurance around the World

For decades, publicly supported agricultural insurance has been considered a failed policy (Hazell et al., 1986) and this is still the view of some authors (Skees, 1999; Cafiero et al., 2007). However, many developed and emerging countries are developing and supporting agricultural insurance as an important tool for farmers seeking to manage risk. The recent international conference on agricultural insurance held in Madrid in March 2010 provided an updated and unpublished report on current developments in agricultural insurance around the world, complementing other earlier published reports (Meuwissen et al., 1999; Bielza et al., 2008a). Mahul and Stutley (2010) have written an up-to-date and comprehensive assessment of agricultural insurance in developed and developing countries.

In Table 19.2 we offer a synthesis of the most recent changes in agricultural insurance in a selection of both developed and emerging countries. Many countries, whether developed or developing, subsidize premiums. There are various countries that are mature in terms of insured crops and acreage including Canada, the USA, Spain and Austria; there are also countries that have experienced significant growth, including India, Russia, Brazil and Argentina. Many EU countries do not subsidize crop insurance (Sweden, the UK, Germany) but provide *ad hoc* payments for disasters and catastrophes (Meuwissen et al., 2008). The Netherlands began offering subsidized insurance in 2009. A number of authors argue that subsidies distort farmers' decisions and generate welfare losses because of asymmetric information (moral hazard and adverse selection) (Skees et al., 2005; Hazell, 2006; Mcleman and Smit, 2006). Others claim that insurance is better than *ad hoc* aid compensation because it involves better screening procedures, more accurate loss adjustment procedures and more rapid compensation disbursements (Burgaz, 2010). Lastly, the EU has approved legislation regulating national aid programs that establishes that only farmers who have contracted insurance policies are eligible for financial aid compensating for losses not covered in the contracted policies and which surpass 30 per cent of average production.

QUANTITATIVE ISSUES WITH CROP INSURANCE UNDER CLIMATE CHANGE

Insurance Premium Forecasts under Climate Change Scenarios

As mentioned in the introduction, we offer results indicating the sensitivity of crop insurance premium to changes in crop yields due to climate change. With this aim, we simulate insurance offered under two scenarios: an actual scenario or control scenario (period: 1960–90) and a climate change scenario (period: 2070–2100; we use the SRES A2 emissions scenario developed by the IPCC, 2000). Simulations are conducted for maize (irrigated), winter wheat and spring wheat (both non-irrigated and autumn-sown). Yields have been calculated for 12 areas in the Iberian Peninsula (see Figure 19.4 – p. 264) using CERES² crop simulation models (CERES-wheat and CERES-maize). The climatic data used in the models were obtained from ten regional climate models (RCMs) from the European project PRUDENCE.³ These models downscale climate change from general circulation models (GCMs).

Moreover, maize yield data were available for a third set of projections using the A2 scenario for climate change. This will allow us to explore the effect of crop adaptation on insurance premiums. In this case, crop adaptation involves the advancement of the maize sowing date by 2.5 months and a shift away from a traditional variety toward a better-adapted one.⁴

An example of the maize yield distribution functions for a particular region (Ebro area) is shown in Figure 19.5 (see p. 264). The functions for the control scenario and the A2 scenarios are both Weibull density functions, and there is a log-logistic distribution for the adaptation projections. These functions result from the best fit (using χ^2 test) based on the outcomes of the ten regional climate group members' climate models and 30 simulation years, both in the control period (1960–90) and in the future climate period (2070–2100).

Table 19.2 Summary of the most recent experience with agricultural insurance around the world

Country	Comments	Recent trend		Comments and source
		Penetration and uptake rate	Indemnities	
Argentina	25% of farmland insured in 2005. Well developed in cereal and oil crops, undeveloped for other crops. 55% of crop insurance contracts are against hail	Insured area grew from 11.2 m ha in 2002 to 17.6 m ha in 2009	Grew with insured area, especially high in 2006–07 season; US\$75 m in 2009	Regulated by general insurance legislation, 26 insurance companies operating (FAO, 2005; Miguez, 2010)
Australia	Drought the major hazard. System works with Farm Management Deposits which allow farmers to save in good years and withdraw funds in bad years	Number of policies grew from 6022 in 1999 to 36 396 in 2009 ¹	N/A	Government provides compensation and support under extreme and infrequent events
Austria	81% of farmland insured against hail. 71% of it also insured against other risks (multi-peril crop insurance)	Between 1985 and 2009, insured area grew from 600 000 ha to 1 249 000.	€75 m in 2009	Droughts no longer assumed as extreme events (Botterill, 2010)
Brazil	Small penetration so far. Small insurance sector in comparison with the size of the agricultural sector. Soybean is 61.5% of farmland insured	Insured area grew from 68 148 ha in 2005 to 6 669 269 in 2009	N/A	Subsidized premia for policies covering hail and frost. Private-public system (Rosenwirth, 2010)
Canada	Dynamic settings, with frequent program changes and innovation. Five programs presently offered to Canadian farmers. The focus is on whole-farm insurance, offering farmers' financial margin stability. 65–70% of farmland insured	Between 2003 and 2009 number of policy-holders diminished, but insured capital grew	Between 2003 and 2009 indemnities grew from €737 m to €1089 m	Government subsidies premia between 40% and 70%. Reinsurance since 2007 (FAO, 2005; Guimaraes, 2010)

Table 19.2 (continued)

Country	Comments	Recent trend		Comments and source
		Penetration and uptake rate	Indemnities	
France	System created in 1964 with the National Guarantee Fund for Agricultural Catastrophes. Since 2003, the French government has impulsed agricultural insurance. Small penetration. MPCl since 2005	In 2008 cereal insured area was near 30%, 15% in wine grapes, 5% in fruits	Indemnities grew between 1998 and 2001	Government subsidizes 35% of all MPCl premia, and 40% young policy-holders (Boyer, 2006; Mortemousque, 2007; Massias, 2010)
Germany	Long experience with hail insurance, generally offered with deductibles. Not MPCl. Governments offer support in case of catastrophes (<i>ad hoc</i> payments). More than 60% farmland insured against hail. Animal Disease Fund	Insured area increased by 130 000 ha between 2000 and 2005	Varies across years, largest in 2000	No subsidies, voluntary, privately offered, 14 insurance companies, 30 reinsurers (European Commission, 2008; Engert, 2010)
India	Mixed public and private programs, with strong support	Between 1999 and 2007 insured area grew from 0.78 m ha to 27.3 m. ha. Number of sold policies grew between 2000 and 2004, but insured area diminished 1 037 000 to 989 000 ha	Indemnities grew from de US\$1.8 m to US\$50,055 m. Indemnities diminished between 2000 and 2005, very low in 2003	Recent introduction of index insurance (FAO, 2005; Raju and Chand, 2008; Pati, 2010)
Italy	Public-private system, with government support, but still low penetration rates. Less than 12% of crop production is insured			Mandatory complete coverage for the same farm. Premium subsidies up to 80% (Cafiero, 2004; Semerari, 2010)

Russia	Federal Agency for Crop Insurance state support since 2003. A fund against catastrophic risks will be set up	Between 2005 and 2008 both the number of contracts and insured area grew (from 12 m. ha to 18.2 m. ha)	Grew from €59.7 m in 2005 to €137.18 m in 2008	Variable government subsidies, always higher than 50%. Insufficient regulatory framework (Kosholkina, 2010)
Spain	Well developed mixed, private-public system since 1978, with government support	Penetration rate about 45% in terms of harvest and animal value. €12 billion of insured capital in 2009, from €6 billion in 2001	Loss ratio 0.96 1980–2009. Maximum losses in 2005, €400 m.	Government subsidies of 50%. Public-private reinsurance (ENESA, 2008)
USA	Well developed, strongly supported by the government. Revenue insurance is the most popular for annual crops, followed by yield insurance with 65% yield coverage. Crop insurance with 85% yield coverage is available for some crops	Frost insurance contracts have diminished, but multi-peril crop insurance contracts have grown	Loss ratio diminished between 1999 and 2007	Government subsidies of 40% (plus administrative costs). Public reinsurance (Callan, 2006; Leach, 2010)

Note: ¹ www.ato.gov.au/business/content.asp?doc=/Content/33432.htm&page=3&H3.

Source: (when no other citation is mentioned): International Conference on Risk and Crisis Management and Agricultural Insurance, Madrid, March 2010.

In simulating the insurance scheme we have assumed a coverage or guarantee level that equals 70 per cent of the average potential yield. The yield distribution function for each area, cropping option and period allows us to compare the premiums for the two periods for each area and crop. We have also studied the change in premiums that occurs when there is a deductible under just the non-irrigated cropping scenarios (for winter and spring wheat). The deductible has been assumed to be a straight deductible equaling the 10 per cent percentile of the yield for each zone, cropping option and period.

The results are shown in Table 19.3. For each cropping option the crop yield changes from one period to the next, as do the results of the variance comparison tests (the period with the highest variance is shown) and the premium value expressed as a percentage for both the control period and the future climate.

Based on the results of Table 19.3 for maize (no adaptation), we observe that CC results in a decrease in yield for the majority of the areas, whereas in the northern and most humid provinces (La Coruña, Lugo and Navarra) an increase in yield is projected. However, when we look at the effect on risk, we see no clear effect of CC: in some cases, the variance is highest for the control scenario, whereas in other cases it is highest for the A2 scenario. The only clear and expected effect is that there is a significant increase in variance, insurance premiums increase and vice versa.

When the adapted strain is used, the yield for maize decreases to a smaller degree or yield increases are higher everywhere; adaptation strategy has a very positive effect on yield averages. The comparison of variance for the adaptation and no-adaptation projections shows that there are more cases in which the control scenario is riskier in the former, suggesting that adaptation is effectively a risk-reducing strategy. The insurance premiums under adaptation decrease in all provinces except for La Coruña and Navarra. In these two provinces, yield increases are projected in tandem with climate change that double under adaptation. A significant decrease in variance results from CC but this decrease is a bit lower when adaptation strategies are used.

Rainfed wheat behaves very differently than maize. Yields are found to increase for spring wheat almost everywhere except for La Coruña and Lugo. The trends in variance and premiums are unclear given that again, in most provinces, the variance is higher with CC. Premiums are not always higher; in fact, they are even lower in most areas (Badajoz, Córdoba², Castilla-León, Ebro, Mancha, Madrid and Navarra). The same is true of winter wheat in Navarra.

In general, CC will result in important changes in insurance premiums for most cropping option–region pairs. Given that these are reference cropping options (irrigated summer crops and rainfed winter and spring crops), these results can be also applied to other similar summer and winter crops.

Sensitivity of Crop Insurance Premium Rates to Climate Uncertainty

Insurance constitutes one possible way of adapting to CC, but the insurance sector will have to adapt to new conditions to ensure that it will continue to be viable (Mills, 2005). Most authors agree that adjusting premiums and coverage levels to changes in loss patterns will not be sufficient because such adjustments would be based on historical data that do not reflect the effects of CC on the frequency and magnitude of extreme events. Insurance ratings are usually based on historical data for an area, climate, type of crop,

Table 19.3 Changes in yield insurance premium rates as a result of CC in the Iberian Peninsula

	Maize (irrigated)						Spring wheat (non-irrigated)						Winter wheat (non-irrigated) ¹					
	No adaptation			Adaptation			No deductible			Deductible			No deductible			Deductible		
	Pre-mium control	Δ (%) yield	Higher variance ² mium A2	Pre-Δ (%) yield	Higher variance ² mium A2	Pre-Δ (%) yield	Higher variance ² mium control	Pre-Δ (%) yield	Higher variance ² mium control	Pre-mium control	Pre-Δ (%) yield	Pre-mium A2	Higher variance ² control	Pre-mium control	Pre-Δ (%) yield	Pre-mium A2	Higher variance ² control	Pre-mium A2
Albacete	0.00	-21.8"	control	0.07	-13.8"	control	0.01	59.4"	A2"	18.53	20.97	14.81	19.88					
Badajoz	0.04	-25.07"	A2	0.34	-3.2"	A2	0.08	56.5"	A2"	19.94	14.93	13.59	8.27					
Córdoba1	0.01	-16.1"	A2*	0.33	-3.1"	A2"	0.15	42.2"	A2"	15.65	20.71	8.96	12.36					
Córdoba2	0.01	-15.2"	A2"	0.46	-2.9"	A2"	0.14	78.7"	A2"	14.21	9.761	7.54	1.81					
Castilla-León	0.78	-19.9"	control"	0.24	-13.9"	control"	0.12	57.1"	A2"	14.20	9.665	6.23	1.70	13.5*	A2	15.29	19.34	9.77 12.37
Ebro	0.59	-25.6"	A2	1.80	-16.8"	control"	0.20	57.2"	A2"	15.07	11.42	6.39	3.48	-9.7	Control ³	19.69	17.09	15.18 14.90
La Coruña	0.98	7.3"	control"	0.17	14.9"	control*	0.20	-27"	control"	19.34	26.9	15.60	19.63	5.7	A2"	9.31	17.83	3.89 14.13
Lugo	4.62	18.5"	control"	0.27	24"	control"	0.21	-24"	control	10.79	13.06	5.39	5.38	19.8"	A2"	10.86	11.86	5.44 5.60
Mancha	0.01	-25.9"	control	0.23	-14.7"	control	0.05	87.8"	A2"	15.24	11.38	2.66	2.76					
Madrid	0.03	-25.8"	A2	0.22	-18.4"	A2	0.10	71.1"	A2"	24.36	18.65	16.43	11.88	-15.3*	control	19.42	17.58	16.20 16.76
Murcia	0.01	-8.6"	A2"	0.07	1.4	A2*	0.03	48.1"	A2*	19.44	21.44	12.12	20.01					
Navarra	6.79	13.1"	control"	0.19	21.6"	control"	0.49	16.4"	A2"	14.65	11.08	11.05	3.49	35.3"	A2"	15.26	11.1	11.52 5.93

Notes:

** $p < 0.01$; * $p < 0.5$.

¹ Winter wheat is currently only cultivated in the northern half of the Iberian Peninsula because the relevant vernalization requirements (the low above-freezing temperatures needed to induce flowering) are not fulfilled in the South, which experiences a milder winter. Under future CC, the North may begin to resemble the South in this respect, increasing the risk of crop failure.

² Results of the variance comparison test (Levene's test) for the two periods: the period of higher variance is shown, together with the level of significance of the difference.

³ In this case, it is not possible to draw a reliable conclusion regarding the significance of the difference between the levels of variance given that each statistic (Levene et al.) leads to a different conclusion: according to Levene's test, the difference is significant with a p -value ≤ 0.01 ; according to the Brown statistic, the difference is not significant; and according to the Forsythe statistic, the difference is significant with a p -value ≤ 0.05 .

expected yield and so forth. If these conditions change due to CC, the data underlying the insurance system will no longer be valid. This is a major challenge for insurance companies (Fosse and Changnon, 1993; Chang and Chen, 2002; Botzen et al., 2009; Giddens, 2009; Hanemann, 2010). In contrast, Maynard (2008) argues that the simple fact of increasing the number of insurees and insurance contracts will have a positive effect on the adaptation process and that it is possible to increase efficiency while maintaining the current insurance system so that there is no real need for changes.

The distribution function for crop yields is a key element of the design of agricultural insurance programs. CC has the potential to modify the distribution function so it becomes necessary to estimate the sign and magnitude of these changes. If such changes are not taken into account, errors will be made in calculating premiums and indemnities. The demand for insurance is also highly dependent on the yield distribution function. Farmers' decisions when choosing their level of coverage, the variety of crops they grow or the number of hectares they grow will be influenced by changes that occur as a result of CC (Chang and Chen, 2002).

In this section, we present some numeric results indicating the sensitivity of insurance premium rates to climatic uncertainties and thus their exposure to actuarial error. The literature on crop insurance indicates the need for the insurance industry to adapt to climate changes. We begin with the simplest case, an asymmetric density function reproducing crop yield.

Assuming yield insurance, the final revenue from a crop (per ha) will be given by the following expression:

$$\tilde{R} = \begin{cases} \tilde{p} \times \tilde{y} & \text{if } \tilde{y} > y_e \\ p_e \times (y_e - \tilde{y}) + \tilde{p} \times \tilde{y} & \text{if } \tilde{y} \leq y_e \end{cases} \quad (19.1)$$

where $(\tilde{p} \times \tilde{y})$ is the product of price and yield when there are no losses, y_e represents the yield guarantee and p_e is the insurance price at which the crop loss is paid. The pure or actuarially fair premium can be obtained as follows:

$$P_f = p_e \int_y^{y_e} (y_e - y)f(y)dy \quad (19.2)$$

with $f(y)$ indicating the yield density function. The analytical calculation of this integral is non-trivial given that it is not defined for all density functions.⁵ Let us assume that $f(y)$ follows a gamma distribution. The pure premium with no deductibles can be calculated as follows:

$$P_f = p_e \int_y^{y_e} (y_e - y)f(y)dy = p_e y_e \int_y^{y_e} f(y)dy - p_e \int_y^{y_e} yf(y)dy = p_e y_e \gamma_{ye} - p_e \int_y^{y_e} yf(y)dy \quad (19.3)$$

where γ_{ye} is the probability that the yield is below the guarantee ($y < y_e$). If the gamma parameters are λ y α , then:

$$P_f = R_e \gamma_{y_e} - p_e \int_{\underline{y}}^{y_e} \frac{\lambda^\alpha}{\Gamma(\alpha)} y^\alpha e^{-\lambda y} dy = R_e \gamma_e - p_e \frac{\lambda^\alpha}{\Gamma(\alpha)} [-y^{\alpha+1} E_{-\alpha}(\lambda y)]_{\underline{y}}^{y_e} \quad (19.4)$$

where $E_{-\alpha}(\lambda y)$ is an exponential integral function. Given that $E_n(z) = z^{n-1} \Gamma(1-n, z)$, then:

$$P_f = R_e \gamma_{y_e} - p_e \frac{\lambda^\alpha}{\Gamma(\alpha)} [-y^{\alpha+1} (\lambda y)^{-\alpha-1} \Gamma(1+\alpha, \lambda y)]_{\underline{y}}^{y_e} \quad (19.5)$$

$$P_f = R_e \gamma_{y_e} - p_e \frac{\lambda^\alpha}{\Gamma(\alpha)} \{ [-y_e^{\alpha+1} (\lambda y_e)^{-\alpha-1} \Gamma(1+\alpha, \lambda y_e)] - [-\underline{y}^{\alpha+1} (\lambda \underline{y})^{-\alpha-1} \Gamma(1+\alpha, \lambda \underline{y})] \}$$

$$P_f = R_e \gamma_{y_e} + \frac{p_e}{\lambda} \left[\frac{\Gamma(1+\alpha, \lambda y_e) - \Gamma(1+\alpha, \lambda \underline{y})}{\Gamma(\alpha)} \right] \quad (19.6)$$

where $\Gamma(1+\alpha, \lambda y_e) - \Gamma(1+\alpha, \lambda \underline{y}) < 0$.

Next, we calculate the effect of an extreme climatic event that may not have been taken into account in the previous calculations. Let us assume that we can statistically describe this event using a binomial $B(1, k)$ where k is the probability that there is no extreme event and $(1-k)$ is the probability of a total crop loss.⁶ Then, yield could be expressed as follows:

$$\tilde{y}_f = \tilde{y}_0 \times \tilde{s}$$

where final yield $\tilde{y}_f$ would equal the ordinary well-known yields given by the gamma ($\tilde{y}_0$) multiplied by a variable $\tilde{s}$ that takes the value 1 when there are no extreme event damages and 0 when there is a total loss according to $B(1, k)$.

The crop revenue (per ha) with yield insurance would be given by

$$\tilde{R} = \begin{cases} \tilde{p} \times \tilde{y}_0 & \text{if } \tilde{y}_0 > y_e \text{ and } \tilde{s} = 1 \\ p_e \times (y_e - \tilde{y}) + \tilde{p} \times \tilde{y} & \text{if } \tilde{y}_0 \leq y_e \text{ and } \tilde{s} = 1 \\ p_e \times y_e & \forall \tilde{y}_0 \text{ if } \tilde{s} = 0 \end{cases} \quad (19.7)$$

The pure premium would thus equal

$$P'_f = p_e \cdot \int_{\underline{y}_0}^{y_e} (y_e - y_0) \cdot k \cdot f(y_0) \cdot dy + p_e \cdot y_e \cdot (1-k) \quad (19.8)$$

and, expressed as a function of the premium P_f obtained above, it would be

$$P'_f = P_f \cdot k + p_e \cdot y_e \cdot (1-k) \quad (19.9)$$

In the following sections, we quantify the sensitivity of insurance premiums to different types of error (variability, including extreme events, and the shape of the distribution

function) that may occur in the future due to uncertainty about the climate. Similar exercises have been performed by Skees et al. (2008).

Scenario 1: uncertainty about yield variability and extreme events

Given that CC can increase the yield variability, it is interesting to explore the impact of changes in variability on yield insurance premiums. With this aim we have analyzed a certain crop whose yield follows a gamma distribution function with an average of 15 Qn/ha (where Qn = quintal).⁷ We have calculated the value of the yield insurance pure premium rates for different coefficients of variation in the gamma distribution function (ranging from 40 per cent to 76 per cent) and keeping the mean constant. We make these calculations for two coverage levels (80 per cent of expected yield in Figure 19.6A and 100 per cent in Figure 19.6B) and three deductible levels: (i) no deductible, (ii) a straight deductible of 15 per cent of the expected yield (2.25 Qn/ha); and (iii) a straight deductible of 25 per cent of the expected yield (3.75 Qn/ha).

To evaluate the magnitude of the possible errors in premium ratings that may result from assuming the wrong coefficient of variation, let us analyze the scenario in which there is no deductible (top curve) in Figure 19.6A. For a 50 per cent coefficient of variation the premium rate would be 10 per cent of the expected yield, but if the coefficient of variation were in fact 63 per cent, the premium would be 50 per cent higher, that is, 15 per cent of the expected yield. Thus the error is equal to 5 per cent of the expected yield. With 100 per cent coverage (Figure 19.6B), the absolute degree of error is similar but the relative degree of error (i.e. the degree of error as a percentage of the premium) is smaller. The error level depends on the deductible levels: whereas it is more or less constant in the case of 100 per cent coverage, it decreases with the deductible but increases in relative terms when coverage is at 80 per cent.

We have also considered a second scenario, one in which we simulate an extreme event that could be associated with climate change. This event would interfere with crop production and has been modeled as a binomial distribution with a 10 per cent probability of total loss combined with yield variability modeled as a gamma distribution. As might be expected, premium levels increase significantly. For a coefficient of variation (CV) of 50 per cent, coverage of 80 per cent and no deductibles, the increase reaches 70 per cent of the premium or 7 per cent of the expected yield (Figure 19.7A). However, the relative increase is much smaller (40 per cent) with 100 per cent coverage (Figure 19.7B).

The premium errors due to incorrect estimation of the CVs are similar to those in the previous case. For the example shown before comparing the results given of the 50 and 63 CVs, the error also equals 5 per cent of the expected yield. Obviously it is lower in relative terms as a percentage of the premium.

These results show the need to adapt insurance premiums to changes in yield variability. If premiums are not properly adjusted, errors can increase and very negative actuarial consequences may ensue. Furthermore, given the concave shape of the curves, the higher the risks are, the greater the actuarial error that can be made. Deductibles seem to provide a small degree of protection, but only for low-coverage insurance.

Scenario 2: uncertainty regarding yield distribution functions

Premiums may not be adapted to real crop risks, not because of an error in the variance estimation but because of errors in the third and fourth central moments in the

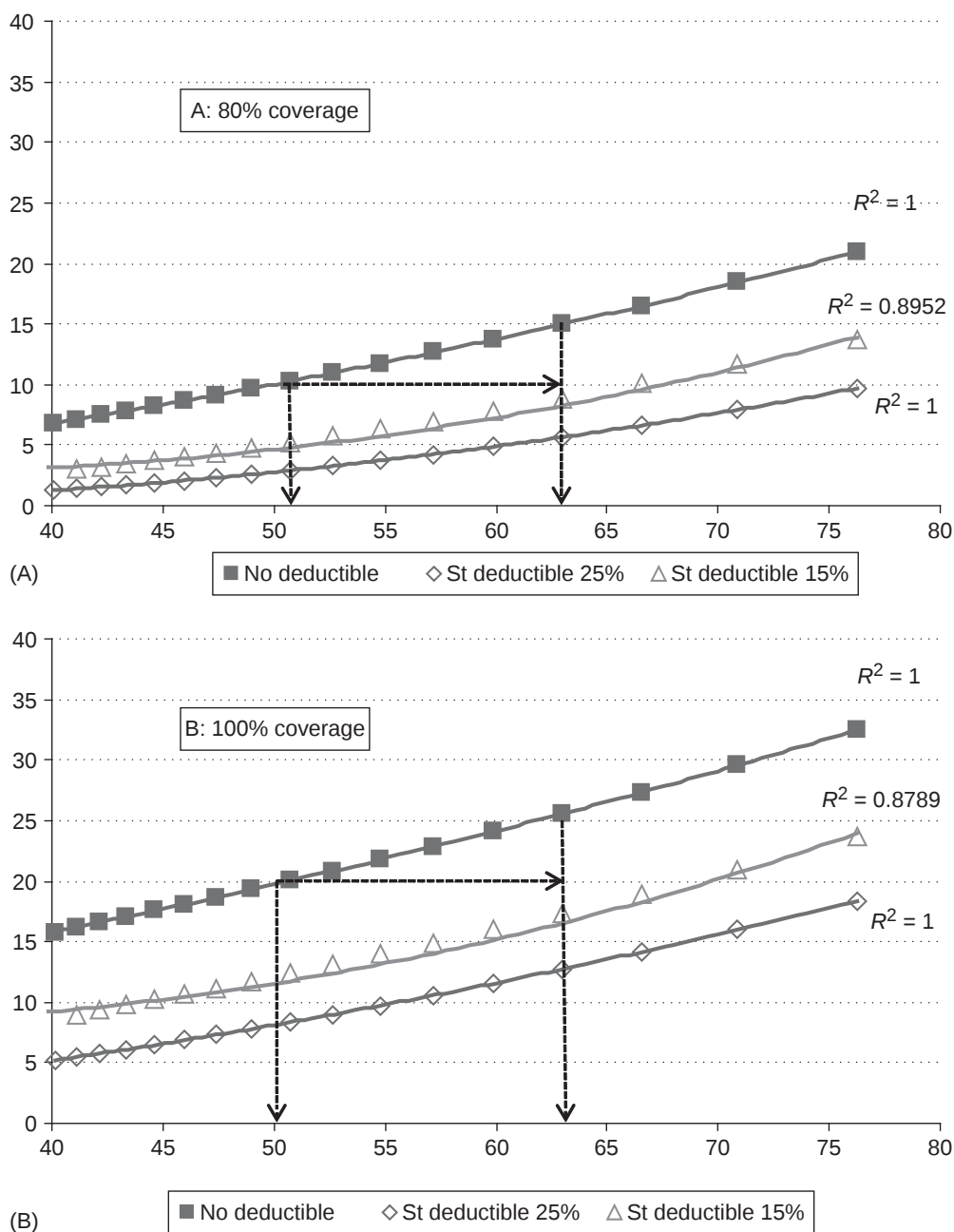


Figure 19.6 Yield insurance premium rates (% of expected yield) against coefficient of variation (horizontal axis): A: 80% coverage; B: 100% coverage

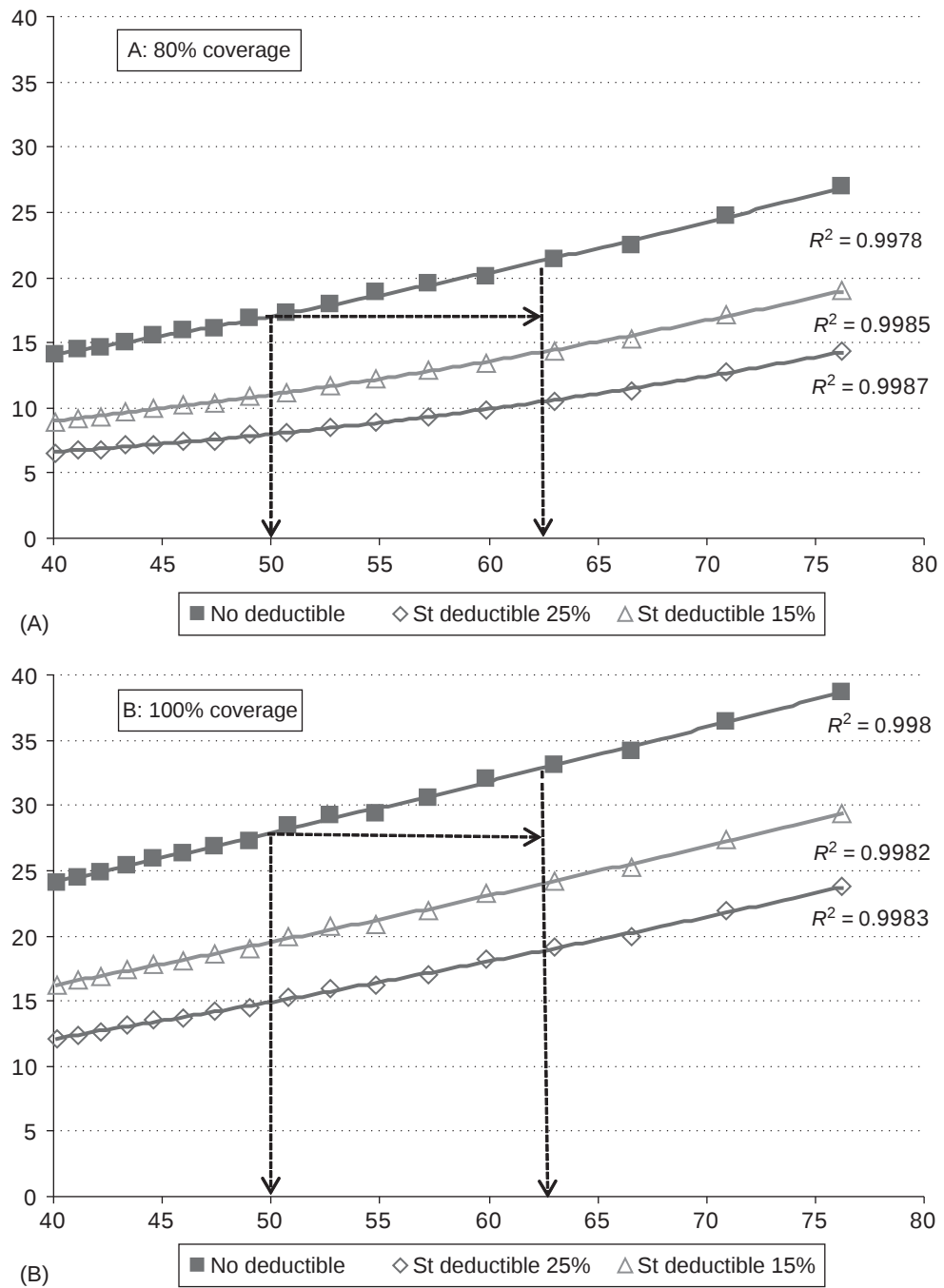


Figure 19.7 Yield insurance premium rates (% of expected yield) against coefficient of variation of gamma distribution (horizontal axis) with binomial extreme events: A: 80% coverage; B: 100% coverage

distribution. This kind of uncertainty can be analyzed by comparing the premiums for the same guarantees but assuming that the yields follow different distribution functions with the same average and standard deviation. To estimate the degree of error that may result from an incorrect assumption regarding the distribution function, premiums have been calculated for different distribution functions for crop yields: gamma, normal, log-normal, Weibull, inverse Gauss, extreme value and Pareto. All of them show almost the same mean and standard deviation, 18.5 Qn/ha and 11.50 Qn/ha, respectively.

Premiums have again been calculated for three deductible levels: (i) no deductible, (ii) a straight deductible equaling 15 per cent of expected yield; and (iii) a 25 per cent straight deductible. The degree of error can decrease or increase in both relative and absolute values with the increase in the deductible (cf., for example, the gamma and normal distributions for examples of decreases and the normal and lognormal distributions for examples of increases in Figure 19.8A – see p. 265). Our comparison of the scenarios featuring 80 per cent and 100 per cent coverage (Figures 19.8A and 19.8B, respectively – see p. 265) shows that the degree of error can be greater even in absolute terms when coverage is lower (with a 0.8 Qn/ha maximum error for 80 per cent coverage versus a 0.6 maximum error for full coverage, occurring under both the extreme value distribution and the Pareto distribution with a 25 per cent straight deductible). The relative premiums also depend on the deductibles: the lognormal distribution in Figure 19.8B features a higher premium than the normal distribution when there is no deductible, but a lower one when there is a 25 per cent deductible. This implies that premium differences between the distribution functions are due to the third and fourth central moments (symmetry and kurtosis).

CONCLUSIONS

Determining whether global agriculture will improve or worsen because of climate change involves considering causation chains in which errors multiply and uncertainties add up. Most models coincide in projecting increasing climatic instability and more frequent extreme events. The insurance industry has become a leading actor and stakeholder in the climate change policy debate. The higher risk associated with global warming is perceived as a business threat that must be faced using standard insurance business strategies together with further vulnerability reduction and mitigation efforts. Social, capital and human vulnerability to climate risks has increased because of increases in risk exposure and economic development. Nevertheless, climate change also offers fabulous business opportunities to the insurance sector, especially in developing countries.

The insurance industry has grown by carefully analyzing previous damage and by exercising prudence in addressing unknown future risk. Climate change is a forward-looking science, and evaluations of damage experienced are generally not as accurate as those that insurers tend to make. Climate scientists and insurance companies must collaborate more closely to more efficiently pursue their own interests (Changnon et al., 1997). Governments and international organizations must actively work to enable closer cooperation between scientists and insurers.

Agricultural insurance is just a small branch of the industry. In most countries in which coverage, penetration and total liability have increased, governments have supported the industry via premium subsidization, direct participation or providing reinsurance. Some

emerging countries, including Russia, India, Argentina, Mexico and Brazil, have shown a sense of determination to increase the role of insurance as a risk management tool for farmers. New technological developments, index formulations, satellite images and mini data loggers have reduced the cost of delivering insurance services to farmers across a wide area.

Most of the challenges posed by slow-onset climate change will require small, gradual adjustments in insurance policies. The challenge facing the agricultural insurance sector is colossal, but it also presents a generous array of opportunities. Greater insurer exposure to climatic risks will create a need for insurers to develop strategies for diminishing their vulnerability. These might include imposing limitations on coverage, increasing premiums, transferring risk through private or public reinsurance and improving the quality of loss assessment. In the field of agricultural insurance the use of indexed products and *in situ* follow-up regarding risk ('data loggers') will increase the efficiency of insurance per monetary unit of premium paid, and will reduce disfunctions due to asymmetric information. However, some hazards, such as those derived from extreme events, cannot be so easily managed unless there is cooperation between the insurance sector and meteorological organizations whose goal is to better understand extreme climate risks. The private sector should work jointly with those agencies responsible for the collection and analysis of disaster data (FAO, 2008). As Skees et al. (2008) state, insurance is not a means of adaptation but can facilitate farmers' adaptation. This can be accomplished by risk layering (where government underwrites the extreme layer) and by ensuring that farmers are offered a safety net that does not discourage them from pursuing other risk management strategies.

Our review of recent developments in agricultural insurance shows that it has changed substantially during recent years in both developed and developing countries. However, the challenge of promoting insurance in developing countries usually cannot be overcome without the intervention of donors and international agencies.

The simulation results regarding insurance premiums under climate change versus the current climate scenario in various zones in Spain show the need for premium adaptation for both irrigated summer crops (maize) and non-irrigated winter crops (wheat). In some cases premiums will have to be increased, whereas in others they may be reduced. The maize adaptation strategy is an efficient instrument for limiting risk, reducing premiums in most cases and increasing average yield.

The Monte Carlo simulations reproducing different levels of error or uncertainty regarding crop risks (variability, exposure to extraordinary extreme climatic events, and risk profile or distribution functions) show significant differences between premiums charged under various circumstances. These sources of errors or uncertainties frequently depend on the coverage level and deductibles used. Deductibles can be used to minimize the consequences of error.

Agricultural insurance is probably less vulnerable to catastrophic risk than are other insurance sectors because there are many possible ways of adapting to climate change in agriculture. First, there are many ways to produce food and fibers with many crops and many techniques at farmers' disposal. Second, the damage experienced in this sector in comparison with that faced by producers of houses or infrastructure (or the potential cost to human life itself) is generally lower. For the poorest regions in the world or those that are most vulnerable to droughts or floods, the current agricultural insurance offered

is inadequate. Index-based risk transfer products have much more potential, especially for those hazards that can be least ambiguously and most easily measured. There are proven advantages in pursuing index and weather insurance in contexts of weak institutional settings and subsistence agriculture.

ACKNOWLEDGMENTS

This work was partially funded by the project 'Minimising uncertainties in the analyses of climate change impact and adaptation in the agricultural systems of the Iberian Peninsula. Tool for Scientific Support to Policies'. MINUNIMAD-CC AGL2008-00385/AGR. Plan Nacional del Ministerio de Ciencia e Innovación. Leading researcher: Professor Inés Mínguez.

NOTES

1. The International Conference of Agricultural Insurance held in Madrid in March 2010 provided a venue for officials from many countries to report the most recent trends (papers can be found at <http://enesa.mapa.es/>).
2. The CERES (Crop Estimation through Resource and Environment Synthesis) family of crop models predicts cereal growth, development and yield. CERES-wheat (Ritchie and Otter, 1985) and CERES-maize (Jones and Kiniry, 1986; Ritchie et al., 1989) are part of the DSSAT 3.5-Cropping System Models (Tsuji et al., 1994; <http://www.icasa.net/dssat/>). The calibration and validation of CERES for wheat and maize were conducted based on Mariscal (1993), Rebollo (1993), Iglesias and Mínguez (1995), Quemada et al. (1997), and López-Cedrón et al. (2005). The effect of CO₂ on photosynthesis and water use was included in the A2 scenario.
3. PRUDENCE stands for 'Prediction of regional scenarios and uncertainties in defining European climate change risks and effects'. This is project EVK2-CT2001-00132, administered under the EU 5th framework program for energy, environment, and sustainable development. <http://prudence.dmi.dk/>.
4. Under the adaptation scenario, it is assumed that the traditional variety PRU001 (a long-cycle cultivar FAO-700 type) will be replaced with a new variety called PRUAD1 that will be better adapted to the climatic conditions predicted for the period 2071–2100. PRUAD1 is an ideotype, so a variety with its characteristics should be sought by geneticists or plant breeders. This ideotype has been studied by Garrido et al. (2011).
5. If $f(y)$ is a beta distribution, the calculation yields a Hypergeometric2F1 function; if it is a gamma distribution, an incomplete gamma function, and normal or lognormal, it will be necessary to evaluate an error function.
6. It would be quite similar to use a binomial $B(1, k')$ where k' would be the probability of a total loss. In such a case, $\tilde{y}_f = \tilde{y}_0 \times (1 - \tilde{d})$ where $\tilde{d}$ takes the value of 1 when there is a damage and 0 when there is not following binomial $B(1, k')$.
7. A quintal (Qn) is a unit of weight equal to 100 kg (about 220 pounds).

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20 An analysis of the choice of livestock species under global warming in African and Latin American farms

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INTRODUCTION

The earth's climate has been gradually warming since the Industrial Revolution due to the burning of fossil fuels and land-use changes (IPCC, 2007a). Researchers find that climate changes today as well as in the future are certain to affect agricultural productivities around the world and could threaten the food security of subsistence farmers in low-latitude developing countries (Reilly et al., 1996; Gitay et al., 2001; IPCC, 2007b). Much of the climate change literature on agriculture, however, has focused on crop failures and paid little attention to livestock production (Adams et al., 1990; Rosenzweig and Parry, 1994; Mendelsohn et al., 1994; Parry et al., 2004; Seo et al., 2005; Schlenker et al., 2005; Kurukulasuriya et al., 2006; Deschenes and Greenstone, 2007; Sanghi and Mendelsohn, 2008; Schlenker and Roberts, 2009). Notwithstanding, animal scientists have reported that livestock productions may be vulnerable to climate change. Higher temperatures are shown to directly affect animal performances such as weight growth, milk production, egg production and wool production (Hahn, 1999; Gitay et al., 2001; Parsons et al., 2001; Mader, 2003). Indirectly, climate changes are known to affect the quantity and quality of livestock feeds and pastures (Reilly et al., 1996; Adams et al., 1999; Sankaran et al., 2005; Butt et al., 2005). In addition, changes in rainfall patterns may affect the severity and distribution of livestock diseases and parasites (Ford and Katondo, 1977; White et al., 2003; University of Georgia, 2007).

Livestock management is an essential component of agriculture around the world (Nin et al., 2007). About two-thirds of the farms in Africa and South America own some livestock species (Seo and Mendelsohn, 2008a). Around 80 per cent of agricultural land in Africa is pasture (World Resources Institute, 2005), while pastures are four to eight times greater than the croplands in major South American countries (Baethgen, 1997). In the USA the value of livestock sales accounts for around 40 per cent of the value of agricultural products sold in a year (USDA, 2002). Economists observe that livestock management decisions are strongly correlated with cropping decisions, which are highly responsive to yearly weather fluctuations (Rosenzweig and Wolpin, 1993; Udry, 1995; Kazianga and Udry, 2006). Recent studies find that management decisions in animal husbandry in Africa as well as in Latin America are highly sensitive to climate variations across the two continents (Seo and Mendelsohn, 2008b; Seo et al., 2009; Seo et al., 2010).

This chapter provides an analysis of the choice of livestock species by individual farmers faced with different climate conditions in Africa and Latin America, the two low-latitude underdeveloped continents widely believed to be most vulnerable to global warming. The analysis is based on surveys from 11 African countries and seven Latin

American countries conducted by Yale University with the help of country teams (Dinar et al., 2008; Seo and Mendelsohn, 2008c). Using multinomial logit models, we estimate fixed climate coefficients in the choices of beef cattle, dairy cattle, goats, sheep, chickens and pigs (McFadden, 1974; Train, 2003). Based on multiple climate scenarios, we then forecast the impacts of climate change on the choice of livestock species in the coming century. The forecasts are extrapolated to the entire continent using the agro-ecological zone (AEZ) definition of the Food and Agricultural Organization (FAO) of the United Nations (FAO, 2003).

THEORY

Depending upon the climate and geography, a farmer decides on whether to specialize in crops, livestock or a diversification of portfolios into both crops and livestock (Seo, 2010a, 2010b). He/she can manage either one animal species or a combination of species (Seo and Mendelsohn, 2008b). Of more than a dozen commonly raised species in the two continents, the most common are beef cattle, dairy cattle, goats, sheep, chickens and pigs (see Tables 20.1 and 20.2). We define a primary species as one that generates the highest on-farm profit. In Africa we find that a primary species accounts for more than 88 per cent of the total net revenue generated from livestock management. We assume that a farmer chooses a primary livestock species to maximize the on-farm net revenue,¹ given the external climate and soil conditions. Alternatively, one can model the choice of a combination of species chosen if one is interested in the specific portfolio of species.

More formally, we assume that the net revenue from species j by farm n can be written as follows:

$$\pi_{nj} = V(Z_{nj}) + \varepsilon_{nj} \quad (20.1)$$

where Z is a vector of exogenous characteristics of the farm and the farmer. For example, Z could include climate, soils, hydrology, topography, access, household characteristics and country dummies. The net revenue function is composed of two components: the observable component V and an error term ε . The error term is not observable to the researcher, but may be known to the farmer.

The farmer chooses species j over all other species if:

$$\pi_{nj}^* > \pi_{nk}^* \quad \forall k \neq j. \text{ [or if } \varepsilon_{nk} - \varepsilon_{nj} < V(Z_{nj}) - V(Z_{nk}) \text{ for } k \neq j] \quad (20.2)$$

The probability for species j to be chosen by farm n is then

$$P_j = \Pr[\varepsilon_k - \varepsilon_j < V_j - V_k] \quad \forall k \neq j \text{ where } V_j = V(Z_j) \quad (20.3)$$

The probability for the n th farm to choose species j is calculated by integrating the appropriate indicator function as follows:

$$P_{nj} = \int_{\varepsilon} I(\varepsilon_{nk} - \varepsilon_{nj} < V_{nj} - V_{nk}, \quad \forall k \neq j) \cdot f(\varepsilon_n) d\varepsilon_n \quad (20.4)$$

where I is the indicator function and f is the probability density function of the error term (Train, 2003). If the density f is assumed to follow an identical and independent Gumbell distribution and the observable component V can be written linearly in the parameters, then the probability can be calculated by successive integrations of the cumulative density functions, which leads to the following succinct expression:

$$P_{nj} = \frac{e^{Z_{nj}\gamma_j}}{\sum_{k=1}^J e^{Z_{nk}\gamma_k}} \quad (20.5)$$

which gives the probability that species j is chosen by the farm n among J animals (McFadden, 1974). After constructing a log-likelihood function from equation 20.5, the parameters can be estimated by the maximum likelihood method employing an iterative nonlinear optimization technique, the Newton–Raphson method. The logit analysis assumes independence of irrelevant alternatives (IIA). However, since all the farms in our sample face the same set of alternatives, the IIA assumption is not a serious limitation. However, it becomes more problematic in predicting future choices of species since a new species can be introduced into the choice set.

The impacts of climate change on the farmer's choice of species j can be measured by examining how selection probabilities for the species are altered by a change in climate. The marginal effect of a change in climate on the probability that species j will be chosen can be obtained by differentiating equation 20.5 with respect to a relevant climatic variable:

$$\frac{\partial P_{nj}}{\partial z_{nl}} = P_{nj} \left[\gamma_{jl} - \sum_{k=1}^J P_{nk} \gamma_{kl} \right] \quad (20.6)$$

DATA

The agricultural data for this study are based on the two continental-level farm household surveys in Africa and Latin America conducted separately by Yale University with the funding from the Global Environmental Facility (GEF), the World Bank and the IICA (Inter-American Institute for Cooperation on Agriculture) (Dinar et al., 2008; Seo and Mendelsohn, 2008c). The CEEPA (Center for Environmental Economics and Policy in Africa) and the PROCISUR are the two regional organizations that helped direct the field efforts of the country teams.

African data consist of farm surveys of agricultural activities during July 2002 to June 2003 from the following ten countries: Burkina Faso, Egypt, Ethiopia, Ghana, Niger, Senegal, South Africa, Zambia, Cameroon and Kenya. Data were gathered from Zimbabwe but were disregarded because of the turbulent political conditions during the survey period. In Latin America, country teams conducted surveys of agricultural households in Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay and Venezuela for farm activities during July 2003 to June 2004. In both Africa and Latin America, countries were chosen to reflect a wide range of climatic zones across the continent given the availability of researchers. Districts within each country were selected to provide as much intra-country climatic variation as possible. Within each district surveys consisted of randomly sampled farms by country experts.

In Africa the five major species of livestock are beef cattle, dairy cattle, goats, sheep and chickens. Other less frequently recorded animals include breeding bulls, pigs, oxen, camels, ducks, guinea fowl, horses, bee and doves. The major livestock products sold are milk, beef, eggs, wool, leather, butter, cheese, honey and manure. The five most common species account for 93 per cent of the total livestock net revenue in Africa (Seo and Mendelsohn, 2008b).

A primary species is defined as one that generates the highest net revenue in the family. The net revenue includes the value of livestock as well as the value of livestock products sold in the survey year. The net revenue is broadly defined to include the value of livestock products consumed by households themselves. A primary species is found to dominate the profit of individual farms. For example, the total net revenue from farms where sheep is the primary species is more than US\$9 million, whereas the total net revenue from other species is less than one-tenth of that from sheep. This is also true of the other four species.

Agriculture is practiced across diverse agro-ecological conditions in Africa. Based on the growing potential of the land, the FAO has defined the 16 AEZs in Africa (Figure 20.1 – see p. 266). The growing season is defined as the period where precipitation and stored soil moisture is greater than half of the evapotranspiration (Fischer et al., 2002). Figure 20.1 shows the AEZs across Africa. Of the 16 AEZs across the continent, the Sahara Desert occupies a vast area in the north. There are also desert zones in the south-western edge of the continent. Just below the Sahara in West Africa is a lowland semi-arid zone, followed by a lowland dry savannah, a lowland moist savannah and a lowland sub-humid zone. From there, the lowland humid forest stretches from Cameroon towards the Central African Republic. Below the humid forest zones are mid-elevation sub-humid zones, mid-elevation moist savannah, mid-elevation dry savannah and mid-elevation semi-arid zones that adjoin the deserts in the southwest. Eastern Africa is composed of deserts, lowland dry savannah, as well as high-elevation humid forests and dry savannah located around Mount Kilimanjaro and the highlands of Kenya. Southern Africa consists of lowland or mid-elevation moist savannah and lowland or mid-elevation dry savannah. Arid, semi-arid zones and deserts which are critically important for livestock management occupy vast amounts of land in Africa. The Sahara Desert and the Sahel, which refers to the semi-arid transition region between the Sahara Desert to the north and wetter regions of equatorial Africa to the south, are arid zones. Arid zones are also located along the eastern coast and in large areas of southern Africa.

In Table 20.1 we calculate the numbers and percentages of the total farms that own one of the five primary species for each AEZ in Africa. Across Africa 7 per cent of the farms use beef cattle as a primary species, 33 per cent of the farms use chickens and 20 per cent use goats, sheep, and dairy cattle, respectively. Beef cattle are chosen most often in deserts, mid-elevation dry savannah, mid-elevation moist savannah zones and mid-elevation sub-humid zones. Dairy cattle are chosen most often in mid-elevation sub-humid zones, high-elevation humid forests and high-elevation semi-arid zones. Goats are favored in lowland moist savannah, lowland humid forests and lowland sub-humid zones. Sheep are the choice species for lowland dry savannah, lowland moist savannah and lowland semi-arid zones. Chickens are favored in mid-elevation moist savannah, lowland humid forests and lowland sub-humid zones.

In South America, five species are most frequently chosen from a dozen commonly raised livestock species: beef cattle, dairy cattle, pigs, sheep and chickens. In Table 20.2

*Table 20.1 Choice of livestock species across agro-ecological zones in Africa**

		High elevation		Lowland		Mid elevation	
		N	%	N	%	N	%
Dry savannah	Beef cattle	–	–	93	5.2	86	14.3
	Dairy cattle	42	53.2	348	19.4	197	32.7
	Goats	3	3.8	461	25.7	70	11.6
	Sheep	14	17.7	577	32.1	62	10.3
	Chickens	20	25.3	316	17.6	187	31.1
Humid forests	Beef cattle	29	5.3	28	5.4	32	6.0
	Dairy cattle	343	62.8	40	7.7	257	48.3
	Goats	46	8.4	161	30.8	65	12.2
	Sheep	46	8.4	106	20.3	51	9.6
	Chickens	82	15.0	187	35.8	127	23.9
Moist savannah	Beef cattle	16	7.6	91	5.8	141	11.1
	Dairy cattle	100	47.4	305	19.5	372	29.2
	Goats	11	5.2	406	25.9	160	12.6
	Sheep	46	21.8	396	25.3	74	5.8
	Chickens	38	18.0	369	23.6	526	41.3
Semi-arid	Beef cattle	–	–	27	6.3	10	8.7
	Dairy cattle	36	73.5	166	39.0	50	43.5
	Goats	5	10.2	87	20.4	12	10.4
	Sheep	1	2.0	114	26.8	30	26.1
	Chickens	7	14.3	32	7.5	13	11.3
Sub-humid	Beef cattle	51	10.3	96	12.4	47	7.1
	Dairy cattle	257	51.7	112	14.4	362	55.0
	Goats	63	12.7	195	25.1	79	12.0
	Sheep	58	11.7	168	21.7	70	10.6
	Chickens	68	13.7	205	26.4	100	15.2

Notes:

N = 5238.

* In the desert AEZ, 120 farms chose beef cattle, 283 farms dairy cattle, 28 farms goats, 55 farms sheep, and 94 farms chickens.

Table 20.2 Choice (percentages) of livestock species in South America

Primary livestock	South America whole	Andes region			Southern Cone region			
		Colombia	Ecuador	Venezuela	Argentina	Brazil	Chile	Uruguay
Beef cattle	48.5(617)	36.6	27.9	57.0	73.7	38.6	36.6	80.5
Dairy cattle	32.8(417)	36.6	55.7	29.9	6.1	43.1	36.6	17.7
Pigs	4.6(59)	2.5	1.6	2.8	4.8	8.8	2.5	–
Sheep	5.8(74)	10.5		7.5	12.3	2.6	10.5	1.8
Chickens	8.1(103)	13.9	14.8	2.8	3.1	6.9	13.9	–

Notes:

1. The numbers in parentheses are the numbers of farms whereon this livestock species is primary.

2. N = 1270.

we show the distributions of the five primary species in South America as a whole as well as in each country. Across all of South America, almost half of the livestock farms have beef cattle as a primary species, while a third has dairy cattle as a primary species. Pigs are chosen by 5 per cent, sheep by 6 per cent and chickens by 8 per cent of the farms. This is in sharp contrast with African farms where beef cattle account for only 7 per cent of the total livestock farms, whereas goats and sheep account for around 45 per cent altogether. The choice of beef cattle as a primary species is especially high in Argentina and Uruguay. Dairy cattle account for the primary species most frequently in Ecuador and Brazil. Pigs are selected most often in Brazil, which is the third largest producer of pigs in the world. Sheep are chosen most often by farmers in Argentina, Chile and Colombia. Chickens are chosen most often by Ecuador, Colombia and Chilean farmers on the Andean mountains (Seo et al., 2010).

Climate data are from multiple sources. Temperature data are obtained from the US Department of Defense satellites (Basist et al., 1998), and the satellite data cover a 16-year period from 1988 to 2004. Precipitation data are obtained from ground weather station measurements (World Bank, 2003; WMO, 1989), and are based on climatic normals from 1960 to 1990. Satellites provide accurate measurements of temperature at the centroid of each district, but cannot measure precipitation directly, because satellite wetness measurements are distorted by water body on the grounds such as lakes, snows and moisture on top of the forests (Mendelsohn et al., 2007).

Soil data are obtained from the FAO digital soil map of the world CD ROM (FAO, 2003), and the soil information is interpolated to the district level using a geographical information system. The data set reports 26 dominant soil types, 116 detailed soil types, soil texture (clay, sandy, or mixed), soil slope (flat, hill, steep) and altitude.

EMPIRICAL RESULTS

Scientists find that livestock productivity is sensitive to climatic factors. Alterations in air temperature, humidity and wind speed are reported to influence animal performances such as weight growth, milk production, wool production and reproduction (Hahn, 1999, Gitay et al., 2001; Parsons et al., 2001; Mader, 2003). Indirectly, changes in temperature and precipitation affect the quantity and quality of livestock feedstuffs such as pasture, forage and grain (Reilly et al., 1996; Adams et al., 1999; Sankaran et al., 2005). In addition, the severity and distribution of livestock diseases and parasites are also known to be climate sensitive, especially in Africa (Ford and Katondo, 1977; White et al., 2003; University of Georgia, 2007).

To model the choice of a primary species by individual farmers, we run a multinomial logit model for African data in Table 20.3. The base (omitted) case is chickens. Most of the coefficients are very significant according to the *p*-values. The three tests of significance of the group of climate variables – likelihood ratio test, Lagrange multiplier test and Wald test – indicate that it is highly significant. This study controls household characteristics in detail. Female heads choose beef and dairy cattle less often than chickens. A larger family is likely to have any of the four species over chickens than a smaller family. Older head of households tend to prefer beef cattle and sheep. Farms with electricity tend

Table 20.3 *A multinational logit model of primary livestock species in Africa*

	Beef cattle		Dairy cattle		Goats		Sheep	
	Coefficient	<i>p</i>	Coefficient	<i>p</i>	Coefficient	<i>p</i>	Coefficient	<i>p</i>
Intercept	-6.8014	0.06	-0.4409	0.84	3.7742	0.17	3.1114	0.26
Temperature summer	0.9589	<0.0001	-0.8047	<0.0001	-0.5232	0.00	-0.2397	0.16
Temperature summer squared	-0.0178	0.00	0.0163	<0.0001	0.012	0.00	0.00546	0.09
Temperature winter	0.00645	0.32	-0.00147	0.75	-0.0119	0.01	-0.0119	0.01
Temperature winter squared	-0.00002	0.32	-0.00002	0.30	0.000064	<0.0001	0.000023	0.22
Precipitation summer	-1.1586	<0.0001	0.4758	0.01	0.0578	0.79	-0.3855	0.03
Precipitation summer squared	0.03	<0.0001	-0.00537	0.22	-0.00053	0.92	0.013	0.00
Precipitation winter	0.0177	0.06	-0.00164	0.80	-0.0138	0.03	-0.0187	0.01
Precipitation winter squared	-0.00009	0.14	-0.00002	0.63	0.000086	0.04	0.000012	0.80
Water flow	-0.0232	0.28	0.1005	<0.0001	-0.0149	0.63	0.0249	0.31
Gender	-0.6066	0.00	-0.3172	0.01	0.105	0.34	-0.1584	0.23
Age	0.0247	0.00	0.0115	0.01	0.00656	0.14	0.0162	0.00
Log size	0.8313	<0.0001	0.9381	<0.0001	0.5597	<0.0001	0.5411	<0.0001
Electricity	-0.6959	<0.0001	-0.0948	0.34	-0.0871	0.31	-0.2358	0.01
Gleysols	-3.2719	0.29	-4.654	0.00	-4.8113	0.01	-4.2108	0.02
Lithosols	-2.0097	0.20	-21.3904	<0.0001	-1.328	0.22	-6.1003	0.02
Luvisols	1.9261	0.40	0.7324	0.86	1.628	0.67	-5.8144	0.50
Arenosols C	-0.8919	0.91	2.3821	0.32	-0.6653	0.79	-0.1645	0.95
Arenosols L	5.9736	0.02	2.2511	0.24	-3.6575	0.07	-7.0523	0.00
Vertisols	1.9	0.33	-0.954	0.84	-1.0692	0.67	-2.4963	0.33
Elevation	0.000771	0.01	0.00062	0.00	-0.00038	0.12	0.000362	0.14
Beef price	-0.00194	0.08	0.00219	0.01	-0.00093	0.36	-0.00137	0.16
Goat price	0.000011	1.00	0.0113	0.14	-0.00402	0.68	-0.0136	0.16
Sheep price	0.0065	0.25	0.00167	0.70	-0.0153	0.01	-0.0103	0.08
Chicken price	-0.2494	0.08	-0.6509	<0.0001	0.2627	0.01	0.6703	<0.0001
West Africa	0.2716	0.19	1.698	<0.0001	-0.0978	0.53	-0.0732	0.65

Notes:

1. The base case is chickens.
2. Tests of the group of climate variables: likelihood ratio test: $p < 0.0001$, Lagrange multiplier test: $p < 0.0001$, Wald test: $p < 0.0001$.

to choose beef cattle and sheep less often. When there is more surface water in a district, farmers are more likely to choose dairy cattle.

Soils and geography turn out to play major roles. When the dominant soil is a Gleysol, farmers are less likely to own dairy cattle, goats or sheep. When the dominant soil is a Lithosol, farmers are less likely to choose dairy or sheep. However, when the dominant soil is an Arenosol, they are more likely to choose beef cattle. In higher elevations a farmer favors cattle over goats and sheep. In West Africa farmers are more likely to choose dairy cattle over chickens.

Many of the price variables turned out to be significant. When the beef cattle price is high, a farmer is more likely to choose cattle, implying a positive own-price effect. When sheep price is high, a farmer is less likely to have goats and sheep. When the price of chickens is high, goats and sheep are chosen more frequently while cattle are chosen less frequently.

Most climate variables are significant at the 5 per cent level. The second-order term of summer temperature has a negative parameter in the case of beef cattle, but a positive one for other species. The quadratic term of winter temperature has a negative parameter for cattle and dairy cattle, but a positive one for goats and sheep. Precipitation variables are highly significant for all the species.

The changes in choice probabilities in response to marginal changes in climate are calculated in Table 20.4. A 1 °C increase in temperature increases the probabilities of choosing sheep and dairy cattle, while reducing the probabilities of choosing beef cattle, goats and chickens. A 1 per cent increase in precipitation reduces the choices of dairy cattle, sheep and chickens, but increases the choice frequency of goats.

To see the distributions of estimated probabilities in detail, we draw the relationships between the mean annual temperature and the probability of choosing a specific species for the five species over the entire range of temperature within the continent in Figure 20.2. The box plots show the means, medians, extremes and 95 per cent confidence intervals at each integer temperature level. The probability of choosing beef cattle is high only in zones where the temperature is less than 14 °C. It drops suddenly as temperature passes beyond the critical level.² The probability of choosing dairy cattle also declines rapidly as temperature increases and is very low when temperature is around 22 °C to 28 °C, after which point it rises slightly. In contrast, the probability of choosing goats and sheep climbs gradually as temperature rises. While the probability of choosing goats begins to fall when temperature exceeds 30 °C, that of sheep continues to increase. In the case of chickens, the estimated probability is hill-shaped with a peak at around 20 °C. A temperature increase may reduce the productivities of beef cattle and dairy cattle seriously (Adams et al., 1999, Butt et al., 2005), which makes goats and sheep more preferable as they can be raised well even in hotter places.

In Figure 20.3, we draw the same figures against the entire range of precipitation in Africa. The choice of sheep declines steadily as precipitation increases.³ The choice of beef cattle does seem to decline in the wettest zones, albeit slightly. The probability of a farmer choosing dairy cattle shows significant fluctuations: it is high at around 80–110 mm per month of rainfall, after which it falls sharply. More rainfall is likely to increase the probability of livestock diseases (Ford and Katondo, 1977, University of Georgia, 2007) and may shift the ecosystem from savannah to forest (Sankaran et al., 2005). In addition, farmers may prefer crops over livestock when there is enough rainfall.

Table 20.4 *A multinational logit model of primary livestock species in South America*

	Beef cattle		Dairy cattle		Pigs		Sheep	
	Est.	<i>p</i>	Est.	<i>p</i>	Est.	<i>p</i>	Est.	<i>p</i>
Intercept	-3.613	0.10	0.8698	0.67	-5.1954	0.18	-7.9958	0.07
Temp. sum.	0.029	0.91	-0.4383	0.08	0.1725	0.64	0.6586	0.14
Temp. sum. squared	-0.00296	0.70	0.00773	0.32	-0.0105	0.35	-0.0197	0.12
Temp. win.	0.1783	0.33	0.1643	0.39	0.0023	0.99	0.0639	0.78
Temp. win. squared	-0.00205	0.70	-0.00121	0.83	0.00427	0.56	0.0074	0.30
Prec. sum.	0.00229	0.75	0.00304	0.67	-0.0138	0.22	-0.0446	0.00
Prec. sum. squared	-8.99E-06	0.60	-8.94E-06	0.60	0.000022	0.45	0.0001	0.01
Prec. win.	-0.0236	0.03	-0.0273	0.01	-0.0199	0.18	-0.0439	0.00
Prec. win. squared	0.000118	0.04	0.000149	0.01	0.000117	0.14	0.0002	0.00
Cambisols	0.034	0.01	0.0429	0.00	-0.1901	0.99	0.0248	0.27
Phaeozems	0.1167	0.99	0.1263	<0.0001	0.1298	<0.0001	0.1079	0.99
Soil Lithosols	-0.0154	0.07	-0.0155	0.08	-0.00487	0.68	-0.0221	0.05
Soil Fluvisols	-0.0149	0.08	-0.0249	0.01	-0.00316	0.78	0.0016	0.89
Soil Luvisols	-0.015	0.05	-0.00538	0.46	-0.0238	0.15	0.0203	0.06
Soil Arenosols	-0.0218	0.09	-0.0417	0.00	-0.0109	0.49	-0.0413	0.21
Soil Xerosols	-0.0335	0.02	-0.0346	0.03	0.0182	0.32	-0.0221	0.21
Texture clay	0.4676	0.01	0.5418	0.00	0.3562	0.20	0.6532	0.04
Flat terrain	-0.0671	0.69	0.1434	0.38	0.0122	0.96	0.3852	0.16
Altitude	-0.00066	0.05	-0.00031	0.33	0.000394	0.48	-0.0001	0.78
Electricity	0.1034	0.63	-0.336	0.12	-0.3911	0.26	-0.1261	0.69
Log family size	-0.0361	0.89	-0.0937	0.72	0.0963	0.80	0.4288	0.27
Log age	1.0595	0.00	0.8561	0.00	0.5777	0.30	0.4594	0.37
Log educ'n	0.6923	0.00	0.2279	0.22	0.4859	0.08	0.2032	0.46
Female head	0.3906	0.06	0.5171	0.02	0.1098	0.72	1.236	0.02
Land tenure	0.4542	0.00	0.3128	0.05	0.2559	0.24	0.615	0.01
Argentina– Uruguay	-0.9426	0.03	-0.0579	0.90	0.1467	0.81	-2.0595	0.00
Chile	-0.1214	0.82	0.422	0.45	1.7611	0.02	0.2789	0.72
Andes	0.2508	0.36	0.4932	0.07	1.7231	0.00	1.0762	0.02

Notes:

1. The base case is chickens.
2. The likelihood ratio statistic to test the significance of climate variables is 1538.57 ($p < 0.0001$).

By contrast, goats and chickens are demonstrated to be chosen more often as rainfall increases. The choice of goats increases rapidly when rainfall exceeds 100 mm per month. Both types of animal may be able to forage more successfully in wetter climates.

The same analysis is conducted on South American farms in Table 20.4. Using chickens as the basis, the table shows four sets of parameter estimates from a multinomial logit model. The likelihood ratio statistic indicates that climatic variables are highly

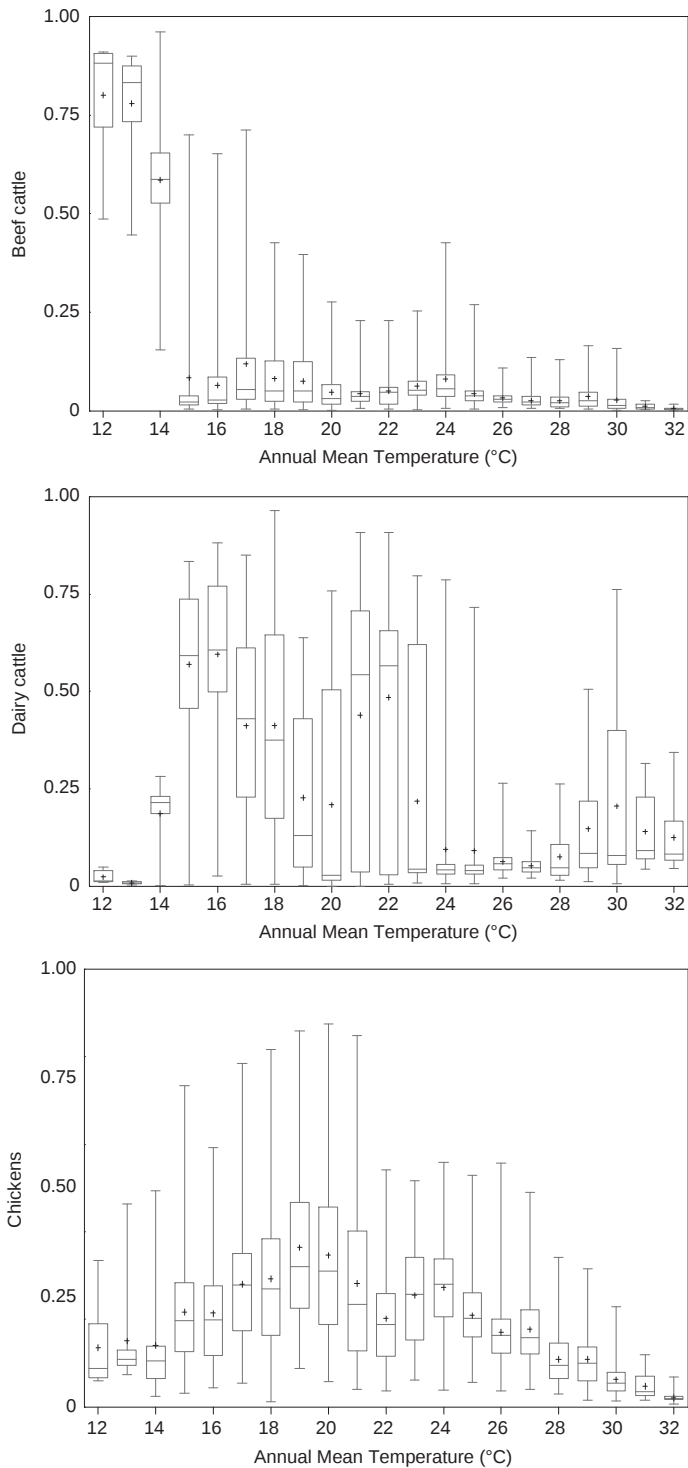
significant factors in livestock species choice. However, many individual climate parameters are not significant. Winter precipitation is significant in the choice of beef cattle and dairy cattle, while summer and winter precipitation are significant in the choice of sheep. Noticeable parameters are negative quadratic terms of summer and winter temperatures in the choice of beef cattle, which signal a high vulnerability of beef cattle to warming. The response of sheep with respect to winter temperature is U-shaped, as for the case of pigs.

Many soil and geographic factors turned out to be important. When the dominant soil is a Cambisol, the farm is more likely to own either beef or dairy cattle. Cambisols are dominant in the mountainous terrains in the Andes and in the Argentina pampas, but rarely found in tropical hot humid zones in northern Brazil (FAO, 2003). When the dominant soil is a Lithosol or Arenosol, the farm is more likely to have chickens. Arenosols are sandy soils and therefore do not yield substantial forage. When the dominant soil is a Fluvisol or Luvisol, the probability that the farm owns sheep increases. When the dominant soil is a Phaeozem, there is a tendency for the farm to own dairy cattle or pigs. If the farm is at high altitude, it is less likely to choose beef cattle than chickens, and when the soil is clay, the farm is more likely to own either cattle or sheep over chickens.

The control variables are family size, gender, education, electricity provision and land tenure of the individual farms. Older farm heads prefer cattle over small ruminants. More educated farm heads prefer beef cattle or sheep. Female farm heads avoid chickens. Farmers who have private land tenure are more likely to have beef cattle or sheep, illustrating that land tenure may capture the effects of land reform in Brazil. These patterns may reflect that (beef) cattle are the most profitable species, but choosing beef cattle may also be a demonstration of least risk taking behavior. These patterns are in sharp contrast to African farms, where farmers are less likely to own beef cattle as a primary species when they are more educated or have private land ownership.

Policy factors are controlled, albeit incompletely, by country dummies. Country dummies capture differences in policies, cultures, trade and country-specific livestock diseases across countries (Anderson, 2009). Since not all the Andean countries have all the species as a primary species, we grouped them into the 'Andes' region. Due to the limited sample and climatic variance in Uruguay, we also aggregated it with Argentina. When compared with Brazil, Argentina–Uruguay farms own fewer beef cattle and sheep, Chilean farms own more pigs and Andean farms are more likely to have sheep, pigs or dairy cattle over chickens. Given the difficulty of measuring the effects of a specific policy intervention, such as a subsidy for ethanol production on agricultural lands, our sample does not include these farms.

Based on the estimated parameters from Table 20.5, we estimate the probability of each species being chosen as a primary species for all the five species. Against the range of temperature found in South America the probability of beef cattle choice shows an inverted U-shaped function while dairy cattle choice shows a U-shaped response. Beef cattle will be chosen by increasingly fewer farms while dairy cattle will be chosen by increasingly more farms as temperature passes the mean temperature of South America. The probability of choosing chickens declines gradually, while that of choosing pigs increases gradually. The probability of selecting sheep will increase with high temperatures. The responses are similar to those found in Africa in Figure 20.2 except for the increasing probability of dairy cattle in hotter zones (Seo et al., 2010).



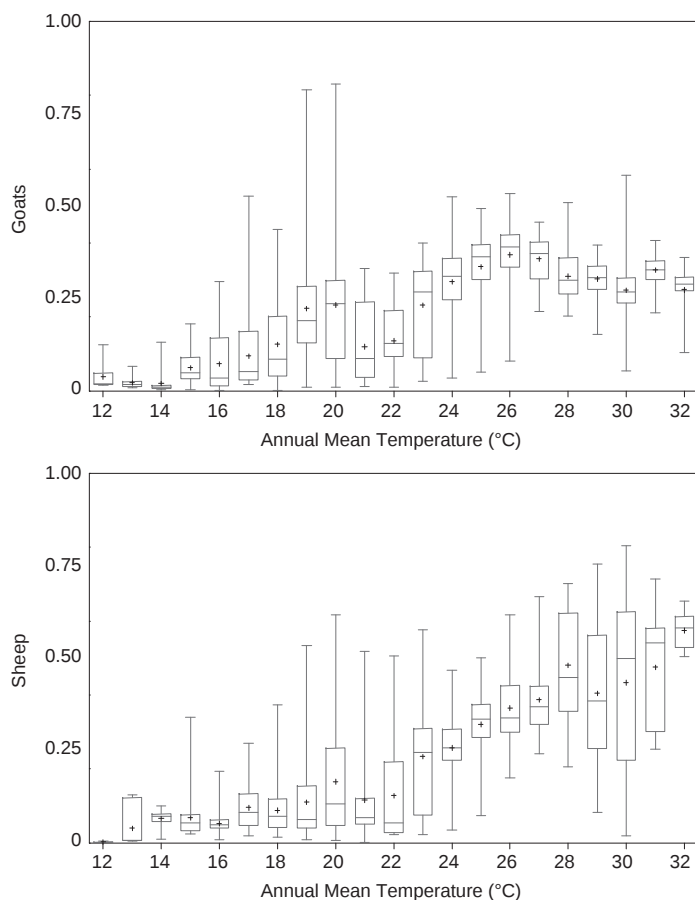
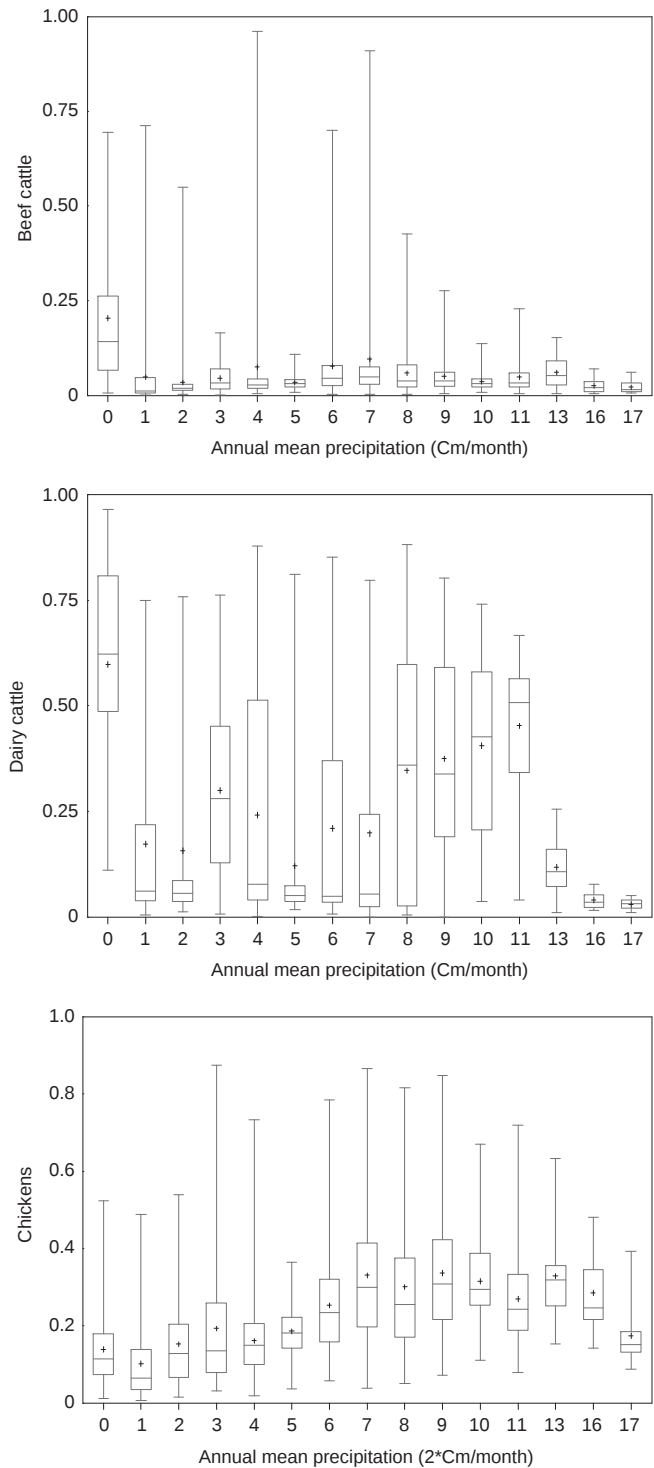


Figure 20.2 Estimated probabilities to choose species over temperature in Africa

Across the variation of precipitation in South America, beef cattle selection diminishes rapidly as precipitation passes the continental mean precipitation level. Sheep selection also declines rapidly until precipitation increases to 200 mm per month, twice the continental average. On the other hand, dairy cattle and chickens are shown to be preferred in substantially wetter zones. Pigs are also chosen equally across the precipitation range. The responses are similar to those in Africa shown in Figure 20.3, except for the large decrease in beef cattle choice and the large increase in dairy cattle choice in wetter zones (Seo et al., 2010).

CLIMATE SIMULATIONS

Based on the climate parameter estimates in Tables 20.3 and 20.4, we simulate the future choices assuming multiple climate scenarios. We examine A1 and A2 SRES (Special Report on Emissions Scenarios) scenarios from the following models (IPCC, 2000):



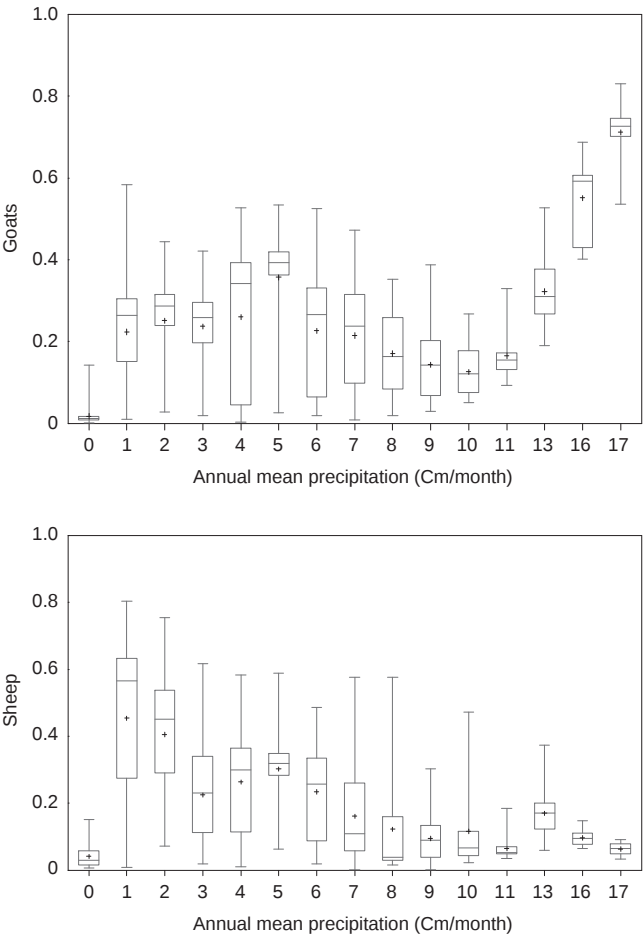


Figure 20.3 Estimated probabilities to choose species over precipitation in Africa

Table 20.5 Marginal effects (percentages): Africa

	Beef	Dairy	Goats	Sheep	Chickens
Baseline	3.04	31.76	21.13	13.94	30.12
Temperature	−0.04	2.42	−0.88	0.38	−1.88
Rainfall	0.01	−0.06	0.15	−0.10	−0.01

Canadian Climate Centre (CCC) (Boer et al., 2000) and Parallel Climate Model (PCM) (Washington et al., 2003). We examine country-level climate scenarios in 2060 for Latin America and in 2100 in Africa. For each climate scenario we add the climate model’s predicted changes in temperatures to the baseline temperatures in each district. We also multiply the climate model’s predicted percentage changes in precipitation to the baseline precipitation in each district.

Table 20.6 Atmosphere–ocean general circulation model climate scenarios

	South America		Africa	
	Present	Half a century later, 2060	Present	A century later, 2100
Temperature (°C)				
CCC	16.5	+2.7	22.9	+6.7
PCM		+1.3		+2.4
Rainfall (mm/month)				
CCC	103	−9.5%	57.9	−20.8%
PCM		+11.9%		25.8%

Table 20.7 Changes in probabilities of livestock species choice by AOGCM scenarios (percentages)

South America (2060)					
Scenarios	Beef	Dairy	Pigs	Sheep	Chickens
CCC	−3.28	−1.51	−0.43	5.61	−0.39
PCM	−1.34	−0.40	−0.20	3.24	−1.30
Africa (2100)					
Scenarios	Beef	Dairy	Goats	Sheep	Chickens
CCC	2.29	11.99	−9.94	11.51	−15.86
PCM	1.21	4.36	1.93	−0.67	−6.83

Table 20.6 shows the predictions. In South America the PCM predicts a 1.3 °C temperature increase, whereas the CCC predicts a 2.7 °C increase by 2060. Rainfall predictions are in opposite directions. The PCM predicts rainfall to increase by 10 per cent by 2060, whereas the CCC predicts rainfall to decrease by 9 per cent. For Africa, the CCC scenario predicts a 6.7 °C increase in temperature while the PCM predict 2.4 °C. The CCC predicts a decrease of rainfall by 20 per cent while the PCM predicts an increase in precipitation by 25 per cent at the end of this century.

We then measure the differences in choice probabilities between today and the future by altering climate accordingly in Table 20.7. First, we turn our attention to Latin America. Under a hot and dry CCC scenario, the choice probability of beef cattle decreases by 3.2 per cent, dairy cattle by 2.3 per cent, pigs by 0.5 per cent and chickens by 0.9 per cent. These decreases are offset by a large increase in sheep ownership by almost 7 per cent. Under the PCM scenario the choice of beef cattle decreases by 1.3 per cent, that of dairy cattle decreases by 1 per cent, that of pigs decreases by 0.3 per cent and that of chickens declines by 0.9 per cent, but the choice of sheep again increases by 3.5 per cent.

These responses would not be uniform across the landscape (Seo et al., 2010). When climate turns hot and dry under the CCC scenario, the choice of beef cattle would decline

across the continent, with the largest changes in Ecuador and Venezuela. Although dairy cattle would decrease at the continental level, large decreases would occur in Ecuador, Colombia and Chile, while increases would occur in Uruguay and Argentina. While the probability of owning sheep increases in all countries, it increases by larger percentages (more than 10 per cent) in the Andes mountain countries of Chile, Colombia, Ecuador and Venezuela. The similarly heterogeneous responses are observed under the PCM scenario.

In the case of Africa, under the hot and dry CCC scenario at the end of this century, sheep would increase by more than 11 per cent while chickens would decrease by more than 15 per cent. Beef cattle would increase by 2 per cent, dairy cattle by 12 per cent and goats would decrease by 10 per cent. Chickens would decrease due to a higher temperature associated with drying, goats due to a drier climate and sheep would increase due to a hotter and drier climate. If, on the other hand, climate in the future turns out to be wetter under the PCM, it would be goats that are favored more often. Consequently the choice of sheep decreases under this scenario.

These adaptive changes taken by individual farmers would differ across AEZs, as shown in Figure 20.4 (see p. 267). Under the CCC scenario, the choice of sheep is expected to increase across all the AEZs except in the deserts. A large reduction of the choice of chickens would occur across Africa. Goats would also decrease across the continent, particularly in humid zones. Beef cattle are expected to increase moderately across all the AEZs except in the deserts, while dairy cattle continue to increase in all the AEZs.

Alternatively, if the PCM scenario comes to pass as shown in Figure 20.5 (see p. 268), goats will increase substantially in sub-humid and humid forest zones in mid and high elevations. The choice of sheep will decrease across all the AEZs except in the lowland dry savannah. Chickens will decrease significantly in high-elevation humid zones and deserts. Beef cattle are expected to be selected more often, especially in high- and mid-elevation dry zones. Dairy cattle will be chosen more frequently in arid zones regardless of elevation, but less frequently in the currently wet zones.

DISCUSSION

This chapter examines the choice of livestock species by farmers in Africa and Latin America who are faced with different climatic conditions. Based on the farm household surveys collected from ten African countries and seven Latin American countries, we model the choice of a primary livestock species against climate and other control variables using multinomial logit models. The most commonly raised species in Africa that are analyzed here are beef cattle, dairy cattle, goats, sheep and chickens. In Latin America, we use pigs instead of goats which are less common.

In both Africa and South America, livestock management is a critical component of agriculture. However, the current portfolio of livestock species that each continent holds is quite different. In Africa, goats and sheep are vastly preferred in the savannahs. They are favored by 45 per cent of the total farms in Africa. Beef cattle account for the choice of around 7 per cent of the total farms. In South America, however, beef cattle are favored by around 50 per cent of the total farms as a primary species. Goat farms are also rare in South America.

The results from the multinomial logit models indicate that climatic variables are highly significant determinants of livestock species choice after controlling for the effects of soils, water flows, geography, household characteristics, prices and country fixed effects. The choice of a primary species across climatic variables varies significantly. As temperatures increase in Africa, the choice of beef cattle and dairy cattle decreases rapidly. On the other hand, the choice of goats and sheep increases steadily. The choice of chickens shows a hill-shaped response with a peak at around 20 °C. With regard to increases in precipitation, sheep are preferred in drier places while chickens and goats are preferred in wetter places. In South America beef cattle and chickens are chosen less frequently by farmers in hot zones, while dairy cattle, pigs and sheep are chosen more frequently. An increase in precipitation reduces the choices of beef cattle and sheep but increases the choices of dairy cattle and chickens.

Based on the multiple climate scenarios we simulate the changes in choice probabilities of the primary livestock species. Under the hot and dry CCC scenario, Africa would increase by about 12 per cent in sheep and dairy cattle, while chickens and goats would decrease by more than 10 per cent, respectively. In contrast, if future climate turns wetter under the PCM scenario, it would be goats that will show an increase of around 2 per cent.

A farmer who wishes to switch to a different livestock species to cope with climate change should take into account the existing climate and soil conditions. For example, a switch to goats under the wet PCM scenario is most likely to succeed in humid zones in mid to high elevations. Similarly, a switch to beef cattle should be occurring most often in dry zones in mid to high elevations.

Under the CCC scenario, South American farmers would reduce beef cattle choice by 3.2 per cent, dairy cattle by 2.3 per cent, pigs by 0.5 per cent and chickens by 0.9 per cent. Instead, farmers increase sheep ownership sharply by almost 7 per cent. Under the wet PCM scenario, farmers again choose beef cattle and chickens less frequently, shifting to an increase in sheep (+3.5 per cent). Under the CCC scenario, the choice of beef cattle decreases across all of South America, but most significantly in Venezuela and Ecuador. Dairy cattle farms are predicted to increase in Uruguay and Argentina, although the rest of the continent will have fewer dairy farms. The choice of sheep will increase in all countries but most noticeably in the Andes mountain countries such as Chile, Colombia, Ecuador and Venezuela.

Although livestock management is often left out, it should be treated as a crucial component in agriculture in any analysis of climatic vulnerabilities and adaptations. In the coming decades the sector is expected to grow rapidly in developing countries due to an increase in consumption (Delgado et al., 1999). Including livestock management into the analysis significantly alters the final estimate of the impact of climate change on agriculture (Seo, 2010a, 2010b) because livestock management is more tolerant of climatic fluctuations than crops. In addition, some species are more resilient to climate change than other species. Finally, the choice of a livestock species is varied across agro-ecological zones. Therefore, in adapting to climate change a farmer should be aware of the AEZ in which the farm is located, in addition to farm characteristics.

Before closing, several qualifying statements are needed. First, this study does not include direct effects of CO₂ doubling which have been shown to cause substantial changes in crop yields (Reilly et al., 1996; Reilly et al., 2000). Second, we assume that a

farmer can adapt to climate change as necessary. For example, a farmer can switch from one livestock species to another as temperature increases or rainfall decreases. Although we do not expect them to be large, there may be adjustment costs involved in the transition (Kelly et al., 2005). Third, farmers may be able to take advantage of the development of a new heat-tolerant breed such as Brahman cattle, which are not included in this study but could become available in the future (Johnson, 1965). Finally, one can alternatively model a combination of livestock species if a specific portfolio of species is of great concern. The portfolio approach leads to similar results to those from the primary species approach reported in this chapter, implying that the choice of a primary species is what matters most to the farms in developing countries.

NOTES

1. Many farms in Africa use their family labor and consume their own products (De Janvry et al., 1991; Moll, 2005). To account for this, this chapter values own consumption at market prices. In the sample, there were no appropriate prices for family labor.
2. The mean temperature for beef cattle farms and dairy cattle farms is 19 °C, for goats and sheep 24 °C, and for chickens 21 °C.
3. The mean precipitation for beef cattle and sheep is 59 mm per month, for goats 68 mm, and for chickens 76 mm.

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21 Climate change, drought and agriculture: the role of effective institutions and infrastructure

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INTRODUCTION

Agriculture is an important source of income and livelihood in many developed and developing countries, and is one of the most vulnerable sectors to climate change. Available evidence suggests that agriculture in many developing countries as well as in several developed countries will be affected by severe negative impacts of climate change. Research studies undertaken so far have focused on the adaptation capacity of the sector, demonstrating how appropriate adaptation strategies can minimize the negative impacts. An implicit assumption of this thesis is that appropriate institutions and infrastructures are in place and they are also very effective in underpinning the necessary adaptation options and strategies. However, this proposition has to be rigorously evaluated. This chapter will develop an analytical framework and methodology that can be used for evaluating the critical linkages between the success of adaptation options and strategies, and the effectiveness of their underlying institutions and infrastructures. The candidate institutions and infrastructures considered here cover some of the major agricultural, market, and water institutions and infrastructures. The methodological focus will be on both the individual and joint impact of these multiple institutions and infrastructures on the effectiveness of different climate change adaptation options and strategies. Following this theoretical exploration and considering drought as a case of climate change, anecdotal evidences will be provided from the literature for the role of institutions and infrastructures in supporting various adaptation strategies, including different agriculture and water management technologies and options.

OBJECTIVE AND SCOPE

The overall objective of this chapter is to develop an analytical framework and empirical methodology for evaluating the critical linkages between the success of adaptation options and strategies, and the effectiveness of their underlying institutions and infrastructures. The specific objectives are to: (a) provide an overview of the literature on climate change impact on agriculture, especially highlighting the role of existing institutions and infrastructures; (b) develop an analytical framework that will capture the specific role of institutions and infrastructures in different channels or pathways through which the impact of climate change is felt on the agricultural sector and transmitted ultimately on to economic welfare; (c) translate the analytical framework into an empirically applicable model of climate change impact on agriculture; (d) discuss how this model can be empirically applied so as to evaluate the role of institutions and infrastructures in

enhancing the effectiveness of adaptation options and strategies in combating the impact of climate change on agriculture; (e) provide anecdotal evidences from the literature on the role of institutions and infrastructures in supporting various adaptation strategies, including different agricultural and water management technologies and options by viewing drought as a case of climate change; and (f) conclude by highlighting the theoretical, empirical and policy implications of the attempted exercise.

The chapter is structured in line with the above-listed set of objectives. As to its scope, this chapter deals with the climate change impact only on agricultural production and its economic effects in the context of a particular region or country. Since the focus is on overall macroscale effects, the scope of the discussion is limited to some of the major impact pathways such as those related to output, employment, income, and so on. Similarly, the candidate institutions and infrastructures considered here for evaluation are also only a few among the many that currently exist. Nevertheless we do consider some of the most important institutions and infrastructures in the agricultural and water sectors. The analytical framework and methodology developed in this chapter, when empirically applied, allows the ranking of different institutions in terms of their contribution to enhancing the effectiveness of adaptation options and in reducing, thereby, the negative impact of climate change on agriculture and farmers. Finally, in the development of the theoretical framework, climate change is considered in a general form. However, in the discussion of the anecdotal evidences, drought, one of the many forms in which climate change can manifest, is taken as a special case.

CLIMATE CHANGE, AGRICULTURE AND INSTITUTIONS: LITERATURE REVIEW

Global temperature has risen by 0.7 °C since 1990 and is continuing to rise at an estimated rate of 0.2 °C per decade. If left unchecked, this implies a global warming of, at least, 1.4 °C (Intergovernmental Panel on Climate Change (IPCC), 2007). As per the Special Report on the Emissions Scenarios (SRES) of the IPCC, unabated rise in CO₂ concentration in the atmosphere can raise the temperature by 1.4–3.0 °C under low-emission scenarios and 2.5–5.8 °C under high-emission scenarios during 1990–2100. Climate change of such magnitude will cause major upheaval in agricultural production patterns both directly via temperature, and also indirectly via the impact on water availability. A warmer climate will accelerate the hydrological cycle by disturbing its key drivers such as precipitation, ice cover, runoff, evaporation and recharge, thereby creating the conditions for a drought–flood syndrome in many agriculturally important regions around the world.

Over the last century, the frequency of heavy precipitation has increased as has that of drought events across different parts of the world. The dry areas have more than doubled since the 1970s while, at the same time, there have been significant decreases in water storage in mountain glaciers. Precipitation is likely to increase in high latitudes and parts of the tropics, but decrease in sub-tropical and mid-latitude regions. Such a precipitation pattern increases the possibility of flash floods in some regions and severe drought in others. However, from an overall perspective, the negative impacts of climate change on water supplies tend to outweigh the positive impacts (IPCC, 2007). As per

the Millennium Ecosystem Assessment (2005), climate change may already be causing long-term shifts in seasonal weather patterns and runoff production that define renewable freshwater availability in any given region. Due to increasing uncertainty as to the availability of water over time and space, the current spatial and temporal patterns of agricultural production will be severely disturbed in many parts of the world. Similarly, the current water management infrastructures and institutions will also prove to be inadequate to cope effectively with the water impacts of climate change.

The review of the literature on climate change impacts in reference to agricultural and water sectors suggests that research attention has emphasized the physical impacts over the institutional and socioeconomic impacts, which have a major bearing on the efficacy of alternative response strategies (Rogers, 1994; Miller et al., 1997). Since private adaptation strategies to climate change will be spontaneous especially at the local level of impacts, the institutional and economic parameters will play a crucial role in determining the adaptive capacity of communities (Adger, 2001). An appropriate institutional response required for an effective adaptation to climate change should originate from the directly affected sector, that is, the agricultural sector itself. Adaptation measures are to be dovetailed into agricultural development programs so that there are enough incentives for the effectiveness of both. The agricultural institutions have to be changed to provide the foundation for the implementation of both the adaptation measures and agricultural development programs.

In the context of the impacts of climate change on the water sector, there is a clear need to build institutional structures for integrated water resource management such as basin-based allocation and management organizations, socioeconomic approaches to water valuation and planning, water rights and entitlements, water information systems and integrated demand- and supply-side management systems (IPCC, 2007). Most of the experts agree that infrastructural modifications and supply and demand management form the core of the water sector strategy for climate change (WaDIMena, 2008; World Climate Conference-3, 2009; Alavian et al., 2009). While the proper institutional response to climate change requires a transnational governance system, the choice of the scale at which institutional issues can be effectively addressed is critical (Adger, 2001). For instance, while mitigation issues involve international institutions such as those related to the UN Framework Convention on Climate Change, the issues of impacts and adaptations involve local- and national-level institutions.

Current evidence suggests that the benefits of many adaptation options validate their costs. For instance, practitioners of disaster management acknowledge that it is typically more cost-effective to invest in disaster risk reduction measures to reduce the impact of a disaster than to provide emergency relief measures once the disaster has struck. *The Stern Review* (Stern, 2007) has, in fact, documented several cases of the economic viability of adaptation options in a number of countries. For instance, in China, the flood control investment of \$3.15 billion undertaken during 1960–2000 is estimated to have averted losses of some \$12 billion. Similarly in Brazil, the Rio flood reconstruction and prevention project has yielded an internal rate of return exceeding 50 per cent. The disaster mitigation and preparedness programs in Andhra Pradesh, India have yielded a benefit–cost ratio of 13.38. In Vietnam, the mangrove planting project aimed at protecting coastal populations from typhoons and storms has yielded an estimated benefit–cost ratio of 52 over the period 1994–2001. It is important to recognize that it is not enough

for the adaptation measures, especially those adopted at the farm or local level, to provide benefits over the costs. Their net benefits have to be substantially higher in terms of improvements in productivity and profitability so that there is strong economic incentive for adoption.

ANALYTICAL FRAMEWORK: THE IMPACT PATHWAYS

Figure 21.1 provides a simplified analytical setting for capturing most of the major impact pathways between climate change and economic welfare in the particular context of agriculture. The impacts of climate change on agriculture are transmitted through a variety of channels. In this impact transmission process, several institutions play an important role in either magnifying or moderating the initial impact of the independent and intermediate variables. Before discussing the impact transmission process and institutional roles, it is useful to note a few important aspects.

First, Figure 21.1 is somewhat abstract and aggregative. It does not cover all the aspects of the intricate and multifarious relationships among climate change, institutions, infrastructures and economic welfare. However, it can be seen that Figure 21.1 covers the most important and policy-wise relevant aspects among these relationships. This is essential in simplifying the analytical framework and sharpening the focus on some of the key relationships.

Second, although climate change is included in a generic format, its specific forms require noting. Specifically, in the context of the agricultural system of a given region, climate change takes the form of either rising temperature with excessive rainfall or rising temperature with deficit rainfall, including delayed onset of rainfall, irregular rainfall pattern and longer dry spells. While the former can lead to floods and waterlogging, the latter can lead to drought and crop wilting. Obviously the exact nature of the impacts on agriculture depends on which climate change scenario is going to prevail in a given context. In this sense, the analytical framework in Figure 21.1 can be used to study the impacts of either the flood situation or drought condition.

Third, from the perspective of the impact of climate change, agriculture can also be represented in a number of forms, such as changes in cultivated area, crop pattern and cropping intensity. Each of these forms can be represented by one or more variables. To evaluate the overall impact of climate change on agriculture, we need to consider the impact on each of these three aspects representing different facets of agricultural production. Cultivated areas can be adjusted to suit the rainfall pattern and water availability. The adaptation in the case of crop pattern includes not only the composition of different crops but also the use of drought-tolerant and early-maturing crop varieties. Similarly, cropping intensity, that is, the extent of multiple cropping in each season and the number of seasons the land is under cultivation, can also be suitably adjusted to respond well to climate change.

Fourth, when considering the impact of climate change on agriculture, water assumes a central role. This is not only because water, both natural and applied, is critical for agricultural productivity, but also because water constitutes the main medium through which most of the impact of climate change will be felt on agriculture in particular and society in general (Stern, 2008).

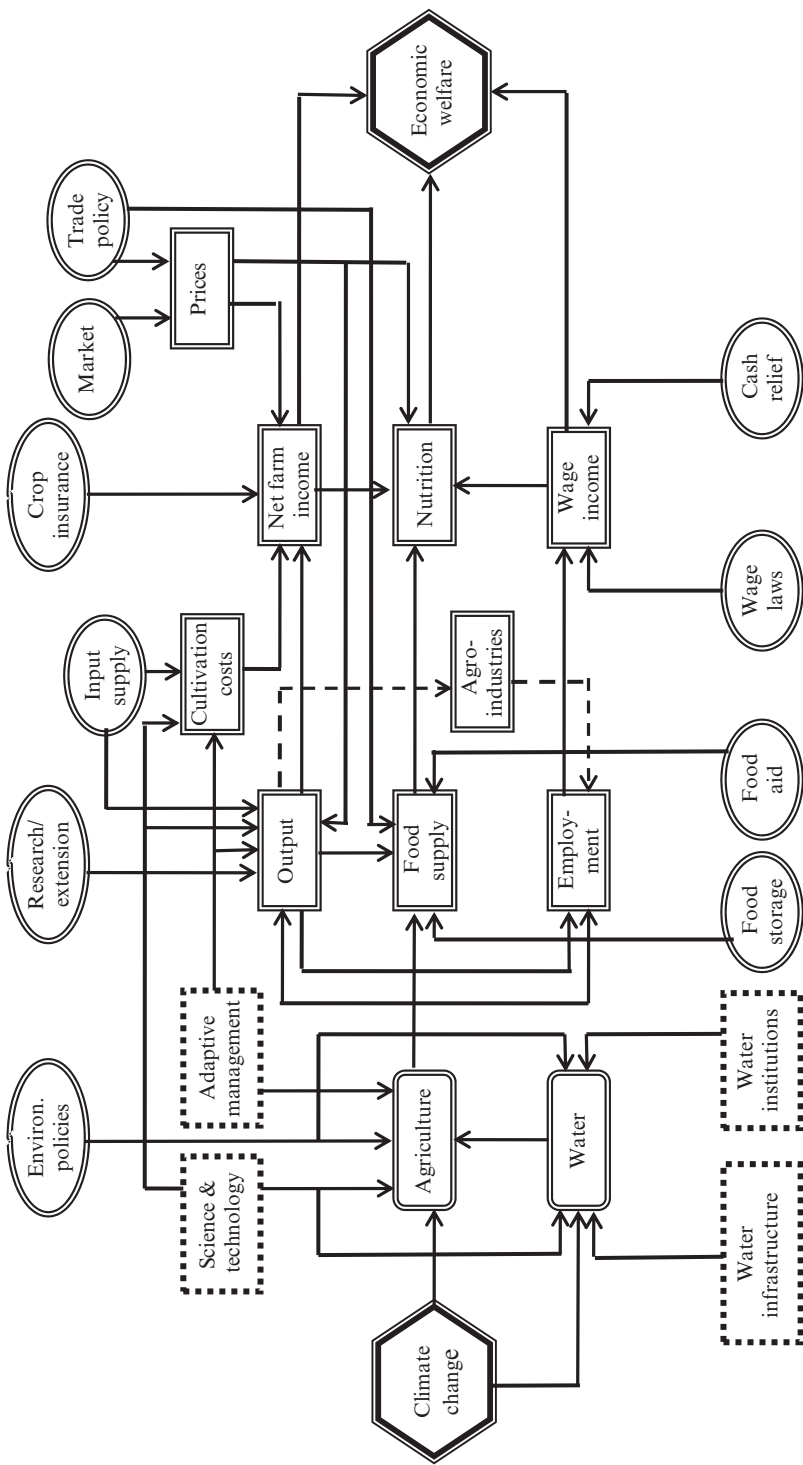


Figure 21.1 Analytics of institutional roles in climate change impact on agriculture

Fifth, for clarity, the initial variable (climate change) and the ultimate impact variable (economic welfare) are placed in Figure 21.1 in hexagons, the immediate variables on which climate impact is felt first are placed in rounded rectangles, the intermediate impact variables are placed in rectangles and the institutional and infrastructural variables are placed in ovals. While most of the impact variables are dependent on the effects of other variables, most of the institutional variables are independent in nature.

Lastly, the items in Figure 21.1 outlined in dots (science and technology, adaptive management, water infrastructure and water institutions) are the adaptive mechanisms by which a given society will try to minimize the negative impacts of climate change. Obviously they represent multiple variables, each of which captures the effects of different adaptation options. For instance, science and technology include options such as crop technologies, irrigation techniques, farming practices and management technologies. Similarly, adaptive management can include multiple cropping, crop diversification, deficit irrigation, zero-tillage and mulching. Likewise, water infrastructures include components such as storage systems, distribution networks, flood protection mechanisms, water harvesting structures and water infiltration points. In a similar way, water institutions cover many legal, policy and organization elements (Bromley, 1989; Ostrom, 1990; Saleth and Dinar, 2004). However, in this study they include specific institutional mechanisms such as water rights system, water markets, water banks, water pricing and user organizations.

In light of the points above, it is straightforward to interpret and understand the analytical framework specified in Figure 21.1. With the definition of suitable variables for each of the impact and institutional variables, all the layers of the impact pathways evident in Figure 21.1 can be formally specified as different equations. Once these equations are empirically estimated with appropriate information, it will be possible to evaluate the relative effectiveness of the different configurations of the set of adaptive options as well as the institutional variables. This is precisely what we intend to do in the next section.

MODELING THE IMPACT OF CLIMATE CHANGE ON AGRICULTURE

To model the impact of climate change on agriculture, we need to provide a mathematical representation of the analytical framework specified in Figure 21.1. For this purpose, let us define first the following variables representing different impact and institutional aspects depicted in Figure 21.1:

<i>CCHANGE</i>	=	Impact of climate change;
<i>CROPPAT</i>	=	Change in cropping pattern;
<i>CROPARE</i>	=	Change in cropped area;
<i>CROPINT</i>	=	Change in cropping intensity;
<i>WATAVAL</i>	=	Change in the water availability for agriculture;
<i>WATINFR</i>	=	Adequacy and effectiveness of water infrastructures;
<i>WATINST</i>	=	Effectiveness or appropriateness of water institutions;
<i>SCITECH</i>	=	Adequacy and effectiveness of science and technology;

<i>AMANAGE</i>	=	Adaptive ability of farm management options;
<i>ENPOLCY</i>	=	Effectiveness of environmental policies related to agriculture;
<i>AOUTPUT</i>	=	Level of agricultural output;
<i>RESEXTN</i>	=	Effectiveness of research and extension system;
<i>INPUSUP</i>	=	Effectiveness of input supply institutions;
<i>CULCOST</i>	=	Level of cultivation costs;
<i>FOODSUP</i>	=	Level of food supply;
<i>TEMPLOY</i>	=	Total employment from both farm and non-farm sources;
<i>FOODSTO</i>	=	Adequacy and effectiveness of food storage system;
<i>FOODAID</i>	=	Adequacy and effectiveness of food aid;
<i>AGROIND</i>	=	Nature and extent of impact on agro-industries;
<i>CROPINS</i>	=	Requirement for crop insurance;
<i>FARMINC</i>	=	Level of net farm income;
<i>NUTRITN</i>	=	Extent of the impact on nutritional level;
<i>APRICES</i>	=	Effectiveness of agricultural prices;
<i>AMARKET</i>	=	Effectiveness of agricultural market institutions;
<i>ATPOLCY</i>	=	Effectiveness of agricultural trade policies;
<i>WAGEINC</i>	=	Level of wage income;
<i>WAGELAW</i>	=	Effectiveness of wage laws and legislations;
<i>CASHREL</i>	=	Requirement of cash relief; and
<i>WELFARE</i>	=	Economic welfare in the agricultural sector.

There are few comments on the variables defined above. First, it can be noted that the variable *CCHANGE* will represent drought if higher temperature is coupled with deficit rainfall or floods if higher temperature is accompanied by excess rainfall. Second, while many variables are qualitative in nature, there are some variables (e.g. *AOUTPUT*, *FOODSUP* and *CULCOST*) that are quantitative. Although the information on this latter set of variables can be collected in quantitative units, this can be done only in an *ex ante* context. As a result, their prediction necessarily involves some subjective and qualitative considerations. Third, as noted in the previous section, the calculation of the value of some variables (i.e. *WATINFR*, *WATINST*, *SCITECH* and *AMANAGE*) is based on the appropriate summation or aggregation of the values of several sub-variables representing different elements or options in each case. For instance, *WATINFR* includes infrastructure components such as storage systems, distribution networks, flood protection mechanisms, water harvesting structures and water infiltration points. Similarly, *WATINST* covers institutional elements such as water rights system, water markets, water banks, water pricing and user organizations.

Given the defined set of variables, the analytical framework specified in Figure 21.1 can be mathematically converted into the following set of 14 equations:

$$WATAVAL = f_1[CCHANGE, \underline{WATINFR}, \underline{WATINST}, \underline{SCITECH}, \underline{ENPOLCY}] \quad (21.1)$$

$$CROPPAT = f_2[CCHANGE, WATAVAL, \underline{SCITECH}, \underline{AMANAGE}, \underline{ENPOLCY}] \quad (21.2)$$

$$CROPARE = f_3[CCHANGE, WATAVAL, \underline{SCITECH}, \underline{AMANAGE}, \underline{ENPOLCY}] \quad (21.3)$$

$$CROPINT = f_4[CCHANGE, WATAVAL, SCITECH, AMANAGE, \underline{ENPOLCY}] \quad (21.4)$$

$$APRICES = f_5[\underline{AMARKET}, \underline{ATPOLCY}] \quad (21.5)$$

$$AOUTPUT = f_6[SCITECH, AMANAGE, CROPPAT, CROPARE, CROPINT, \underline{RESEXTN}, \underline{INPUSUP}, APRICES] \quad (21.6)$$

$$FOODSUP = f_7[CROPPAT, CROPARE, CROPINT, AOUTPUT, APRICES, \underline{FOODSTO}, \underline{FOODAID}] \quad (21.7)$$

$$CULCOST = f_8[SCITECH, AMANAGE, \underline{INPUSUP}] \quad (21.8)$$

$$AGROIND = f_9[AOUTPUT] \quad (21.9)$$

$$TEMPLOY = f_{10}[CROPPAT, CROPARE, CROPINT, AOUTPUT, AGROIND] \quad (21.10)$$

$$FARMINC = f_{11}[AOUTPUT, CULCOST, \underline{CROPINS}, APRICES] \quad (21.11)$$

$$WAGEINC = f_{12}[TEMPLOY, \underline{WAGELAW}, \underline{CASHREL}] \quad (21.12)$$

$$NUTRITN = f_{13}[FOODSUP, FARMINC, WAGEINC, APRICES] \quad (21.13)$$

$$WELFARE = f_{14}[FARMINC, NUTRITN, WAGEINC] \quad (21.14)$$

We can note certain important features of the equation system (21.1) to (21.14). First, the 12 underlined variables in the equation system relate to institutions (*WATINST*, *ENPOLCY*, *RESEXTN*, *INPUSUP*, *FOODAID*, *CROPINS*, *AMARKET*, *ATPOLCY*, *WAGELAW* and *CASHREL*) and infrastructures (*WATINFR* and *FOODSTO*). Second, the equations display both sequential linkages as well as simultaneous relations among them. Third, of the 29 variables in the system, 14 are dependent (endogenous) variables and 15 are independent (exogenous) variables. The dependent variables are involved in capturing and transmitting the impact of climate change, the effect of the four main adaptation mechanisms and the role of institutions and infrastructures throughout the entire system, captured finally by the ultimate dependent variable, which is *WELFARE*. The independent variables include the 12 institutional variables in addition to the climate change variable (*CCHANGE*), the science and technology variable (*SCITECH*) and the adaptive management variable (*AMANAGE*).

An important econometric property of the equation system (21.1) to (21.14) with considerable implications for the quality of empirical results has to be noted. Given the configurations of endogenous and exogenous variables, all the equations in the system satisfy the rank and order conditions needed for their identification and unbiased estimation (Kennedy, 1987). The order condition requires that, for each equation, the number of excluded exogenous variables is greater than the number of included endogenous variables minus one. This condition ensures the exclusion of enough exogenous variables to serve as instruments for estimating the endogenous variable remaining dependent in each equation. The rank condition, though quite technical, requires that all equations are distinct such that none of them can be formed from a linear combination of any other equations in the system (Kennedy, 1987, pp. 138, 142).

Because of the sequential linkages within the equation system, the effect of a marginal change in any of the independent variable on any of the dependent variables in the previous equations will be reflected in all of the subsequent equations, where that dependent variable enters as an independent or explanatory variable. This is an important structural feature, which will be utilized to track down the effects of the adaptation options as well as the institutional and infrastructural elements. This evaluation can be performed

by converting the equation system into a single but long chain equation, where each of the equations in the system is appropriately embedded. By differentiating this single equation with respect to each of the 15 independent variable noted above, it is possible to evaluate the relative effectiveness and performance of the different institutions, infrastructures and adaptation options in terms of their individual and joint effects within the impact transmission process.

While the analytical and practical utility of the equation system specified in (21.1) to (21.14) is clear, the main challenge lies in the generation of information needed for the empirical estimation of the model. Considering the *ex ante* nature of the impact process, it is hard to get observed or quantitative information on many variables in the system. Even if we can have observed information on some variables, they relate to a past situation, making them less appropriate to capture the future state. It is still more difficult to get objective data on the institutional and infrastructural variables, especially on their diverse roles within and across the impact pathways. The deficiency or lack of observed data on most variables does not, however, mean a complete absence of information. In fact, highly relevant information is constantly processed, coded and stored as perceptions in the minds of individuals involved in the development process, either as planners and beneficiaries or simply as evaluators or observers (Saleth and Dinar, 2004).

Such real, but latent, information embodied in individuals can be tapped through carefully designed and conducted stakeholder surveys. Interestingly, this form of information has many desirable properties often overlooked in the so-called objective or observed data. For example, unlike the observed data characterizing a past and static situation, the perception-based data, when elicited carefully, can be a synthesis of the objective, subjective and aspiration-related factors as well as the *ex ante* and dynamic elements (Saleth and Dinar, 2004, and 2008). The use of such perception-based data also has a strong theoretical legitimacy and considerable empirical precedence. The theoretical legitimacy comes from the subjective nature of institutions (Douglas, 1986; Ostrom, 1990), stakeholders as ‘agents of institutional change’ (North, 1990) and the human practice of ‘adaptive instrumental evaluation’ (Kahneman and Tversky, 1984; Bromley, 1985). The empirical precedence includes studies on institutional analysis (e.g. Gray and Kaufman, 1998; Barrett and Graddy, 2000; Kaufmann et al., 2006) and impact assessment (e.g. Neubert, 2000; Coudouel et al., 2006).

Given the rationale for using perception-based data, the next steps for their collection involve a clear delineation of the spatial context as well as a careful selection of a sample of stakeholders. With efficient survey tools and appropriate sample of stakeholders, it is possible to collect considerable information for the empirical evaluation of the model specified in equations (21.1) to (21.14). Such information will usually be recorded as scores on a scale of 0–10, where zero means no effect and 10 means the highest possible impact. In the case of quantifiable variables (e.g. output, income, employment and food supply), these scores can be converted into quantitative equivalents by using the range of minimum and maximum values observed in the sample. However, in cross-sectional regression and when using qualitative variables requiring performance scores, the results will not be qualitatively different in regard to the nature and sign of the coefficients of variables, regardless of whether the scores or quantitative equivalents are being used.¹

DROUGHT, ADAPTATION OPTIONS, INSTITUTIONS AND INFRASTRUCTURES

The analytical framework depicted in Figure 21.1 and its equivalent mathematical representation in terms of the system model specified in equations (21.1) to (21.14) consider the impact of climate change in generic terms. As climate change has not yet happened on a major scale, the evaluation is essentially *ex ante* and futuristic in nature. However, some of the potential impacts of climate change can be evaluated by considering the *ex post* impacts of and adaptation to droughts. Droughts are one form or a subset of climate change and they are already observed widely in many parts of the world. For managing the agricultural impacts of droughts, farmers are already using the four adaptation options specified in Figure 21.1, that is, the use of science and technology, reliance on adaptive farm management practices, modification in water infrastructures and changes in water institutions. As we evaluate these adaptation options, which are currently adopted for managing agricultural impacts of droughts in various contexts, we can learn a great deal about farmers' likely response to the futuristic event of climate change. In this section, we will provide some anecdotal evidences both for the way farmers use the four adaptation mechanisms, that is, science and technology, adaptive farm management, water infrastructures and water institutions, as well as the critical role of other agricultural and rural institutions in the particular context of managing the agricultural impacts of droughts.

The main way drought affects agricultural production is by substantially eliminating or reducing water availability, either directly by rainfall failures and curtailed water supply, or indirectly by increasing temperatures that induce higher evapotranspiration rates or both. Such drought situations can affect both crop and livestock production, thereby reducing the farm income. A useful synthesis of various aspects of climate interactions in agricultural and livestock production is provided by Mendelsohn and Dinar (2009, pp. 10–31), and in several chapters in this *Handbook* (e.g. Chapters 3, 18 and 20). Farmers can counter the impacts of droughts by increasing on-farm water use efficiency by using water and crop technologies as well as by relying on adaptive farm management strategies to minimize the risks and hazards associated with drought and climate change. Various technological options for adapting the crop and irrigation systems are available to farmers, depending on their crop types, farm sizes and irrigation conditions. In this section we will provide a limited number of examples to illustrate how farmers currently utilize various adaptation methods to counter the agricultural impacts of droughts in their regions and how such adaptation methods can be used for countering the future impacts of climate change.

Role of Science and Technologies

Use of drought-resistant crop varieties is an important example that shows how farmers can utilize technology to adapt their production to lower water supply regimes as well as increase water use efficiency and productivity. The main mechanisms that determine drought resistance are the maintenance of high plant water status during stress, the keeping of plant function at low plant water status and the recovery of plant water status and plant function after stress (Zhang et al., 2005). Bioengineering research in

China has shown that the s-Dwarf wheat variety possesses all these traits and displays a remarkable ability to both survive and recover from drought with 80 and 48 per cent survival and recovery rates when compared to other varieties, when subjected to dehydration and rehydration treatments (Zhang et al. 2005). Similarly, in the rain-starved region of Northern Sudan, while the drought-tolerant sorghum hybrid Hageen Dura-1 has increased yields up to 150 per cent higher than the traditional sorghum cultivars, another drought-tolerant sorghum hybrid, NAD-1, has increased the yield four to five times higher than the national sorghum average (Ejeta, 1988) and ten times the average yield for farmers in Niger (Kapran et al., 1995).

Soil water potential can be measured using a tensiometer, which measures the pressure potential of soil and is an indicator of soil-water status (de Assis de Souza Filho and Brown, 2009; Paramasivam et al., 2000). Tensiometers offer constant soil-water measurements at varying depths within the soil profile, allowing farmers to calculate the amount of water traveling past the root zone. There are significant opportunities for water conservation in crops where a substantial amount of water may be percolating below the root zone, which is considered as a loss (Paramasivam et al., 2000). Quantifying the volume of water that percolates past the root zone using measurements of soil-water potential is a technically efficient and economically useful tool that can offer substantial water savings in agriculture.

Role of Adaptive Management Strategies

On-farm crop and irrigation management is an alternative to the implementation of technology to increase water productivity and can be accomplished using a variety of methods. Precision agriculture (Bongiovanni and Lowenberg-Deboer, 2004), tillage method conversion (Unger et al., 1991), contingency crop planning (Wilhite, 2000b), irrigation scheduling (Pereira, 1999), wastewater reuse (Asano et al., 1996) and conjunctive use of surface and groundwater (Wrachien and Fasso, 2007) are all agricultural crop and water management options that have resulted in increases in water use efficiency and water productivity. Farmers in the Indian state of Madhya Pradesh have coupled the varying water demands of crops with regional climate differences in precision agriculture to better exploit the natural precipitation in dryland farming. Similarly, traditional farmers in Oaxaca in Mexico adjust to drought conditions by selecting maize varieties suitable for expected precipitation for a given region (Wilhite, 2000b). Compartmentalization of crop species in terms of agro-climatic zones based on rainfall and soil type ensures the maximum efficiency in the exploitation of available precipitation in dryland farming. Utilizing regional agro-climatic variations for crop suitability has shown considerable promise to Indian farmers, as the average crop yield was four times higher than the traditional approach to crop planning (Singh and Ramana Rao, 1998).

Another method for conserving and utilizing available soil moisture relates to conservation tillage. Conservation tillage systems are methods of soil tillage that leave a minimum of 30 per cent of crop residue on the soil surface and reduce or eliminate secondary tillage. Although the benefits of using conventional tillage versus conservation tillage are dependent upon regional conditions (Moreno et al., 1997), research has shown that in drought-prone Mediterranean climates where the conservation of available

precipitation as soil moisture for dryland farming is the principal means of agricultural water supply, the benefits of conservation tillage far outweigh those of conventional tillage systems. Unger et al. (1991) have illustrated that conservation tillage results in increased water storage capacity within soil. Moreno et al. (1997) showed that greater water use efficiency and significantly higher crop yields resulted under conservation tillage compared with conventional tillage methods. This makes conservation tillage an extremely significant method of increasing water productivity and reducing the risks associated with drought-oriented climate change in the agricultural sector.

Contingency crop planning is a method of crop management that farmers have employed to reduce the risks and hazards associated with water deficit and drought. Depending on the timing of the water deficit, various methods of contingency crop planning can be implemented to reduce the magnitude of the negative effects of droughts. When a drought or water deficiency can be anticipated prior to planting, mixed or intercropping may increase the chances of crop survival. Indian farmers plant a variety of staple foods in the anticipation of drought, which provides them with insurance against an entire crop failure, and may even replace the long duration high-yield crops with short duration low-yield crops for risk reduction (Wilhite, 2000a). If delayed precipitation is experienced, a substantial time after sowing, crop thinning can reduce the potential risks experienced by farmers. Quantitative calculations of risk reduction by crop thinning depend on the particular crop. However, research conducted by Sastri (2000) has shown that the thinning of sorghum in every third row at the onset of drought can increase yield almost twofold. Similarly, the research conducted by Venkateswarulu (1992) on drought-affected sorghum suggested that thinning can increase crop yield up to fourfold.

Role of Irrigation Practices and Infrastructural Modifications

Modernization of irrigation systems may be one of the most feasible technological options that farmers can utilize to increase water use efficiency. A comprehensive review of irrigation system modernization and its role in increasing water use efficiency can be found in Faci et al. (2000) and Playan et al. (2000). Significant increases in crop yield and considerable decreases in irrigation water demand have been obtained when sprinkler irrigation systems replace flood irrigation methods. This is the direct result of an enhanced irrigation uniformity and better control over depth of drainage (Playan and Mateos, 2006). On-farm water use efficiency has improved up to 90 per cent in the case of sprinkler systems observed in north-eastern Spain (Dechmi et al., 2003). Research conducted along the King Abdullah Canal in Jordan shows similar results, with greatest irrigation efficiency coming from pressurized systems, which have shown a 20 to 30 per cent greater project efficiency over that of the traditional non-pressurized surface irrigation systems. The increase in water supply in pressurized systems is attributed to the reduction of losses due to evaporation, deep percolation and surface runoff (Battikhi and Abu-Hammad, 1994).

The creation of water harvesting systems is one method of increasing water availability and use efficiency under scarce water conditions. For instance, rainfall cistern systems have been shown to reduce precipitation runoff by 45–48 per cent in the Chhattisgarh region of India while, at the same time, increasing the productivity of soybean and rice by 63 and 76 per cent respectively (Wilhite, 2000b). This system uses a series of alternating

sunken and raised beds in which crops are planted based on their consumptive water needs. Highly consumptive crops such as cotton and maize are placed in the sunken beds whereas low-consumptive crops are placed in the raised beds. The excess rain from the raised beds automatically flows into the sunken beds, ensuring the water flow into the adjacent crop and thereby reducing the potential for surface runoff. In the Uda Walawe area of Sri Lanka, concrete canal lining has increased available water for consumptive use by reducing groundwater seepage by 50 per cent, resulting in a significant extension of irrigated land in the area with enhanced crop cultivation for local food supply (Meijer et al., 2006). Similar results are obtained in Jordan, where sand trenches increase the water storage capacity of clay soil by decreasing precipitation runoff, resulting in the storage of 99 per cent of precipitation (Majed et al., 2000).

Irrigation scheduling provides farmers with management tools to irrigate according to crop water demand, which is measured using soil or plant-based monitoring systems. There is a variety of methods to measure the plant or soil-water status directly. The methods of measurement that give a quantitative assessment of plant-water potential are the leaf pressure bomb (Tyree and Hammel, 1972) and the leaf porometer (Bravdo, 2006). Measurement of soil-water potential can be achieved by using tensiometers (Li et al., 1989) and time domain reflectometry (Zegelin et al., 1989). One drawback to the direct measurement of plant-water potential is that measurements are traditionally taken from the plant leaf. This measurement of plant-water potential does not serve as an effective indicator of small changes in soil-water status, which is all that is needed to induce plant wilting. Research conducted by Bates and Hall (1981) illustrates that there is a clear disconnect between measurements of leaf-water potential and small changes within soil water potential that induce stomatal closure and subsequent plant wilting. Considering that plant-water status is ultimately a reflection of soil-water status, measuring soil-water potential eliminates many physiologically induced discrepancies between actual plant-water status and leaf-water measurements, using leaf water potential.

Role of Water Institutions

In the face of drought and climate change, increased water conservation and water productivity must not only be achieved within the agricultural sector, but also within the water sector as a whole through a change and adaptation in water institutions. Water institutions are defined here as encompassing all the water-related laws, policies and organizations that govern the whole gamut of water-related activities such as water development, allocation, use and management (Saleth and Dinar, 1999, 2004). Each of the main components of water institutions, that is, water law, water policy and water organization, possesses various mechanisms to mitigate the effects of drought before its onset, during the drought period and after the dissipation of drought effects. While water and irrigation-related technologies will play a direct role, water institutions play an indirect but indispensable role in providing the economic incentives and organizational basis for the adoption of existing technologies as well as the development of new technologies. Let us highlight the role of some of the major institutional mechanisms in creating the necessary economic incentives for the development and applications of technologies and water management strategies to combat the negative water effects of droughts on agriculture.

The adoption of supply augmentation and pricing policies allows the rearrangement of water supply and distribution so as to manage water demand. These policies have the ability to reallocate available water supply so that the water demands of high-value activities are met first, and augment water supply by curtailing the water allocation to less-valued agricultural production during the times of drought. Supply augmentation can also be achieved using various mechanisms of water allocation, all of which seek to achieve maximum economic efficiency, increase water productivity and conserve available water resources. Water supply augmentation is achieved by reducing water wastages and increasing supply from water reuse and recycling. Under a priority system, supply is augmented based on maximizing societal benefit by supplying water according to established priorities of water use. Priority is usually given to the meeting of basic needs such as municipal water uses and allocating the remainder between secondary and tertiary priorities, especially when water is shared between various sectors such as municipalities and agriculture (de Assis de Souza Filho and Brown, 2009).

Water pricing schemes also aim to replicate the economically efficient allocation of water in a free-market system based on the willingness to pay of users. However, water pricing policies face many drawbacks and practical difficulties and also require infrastructural modifications to enable volumetric water allocation. Pricing policy is ineffective when there are uncertainties over the willingness to pay of water users, known as 'demand uncertainty', and also when there are seasonal fluctuations of water supply, known as 'supply uncertainty' (de Assis de Souza Filho and Brown 2009). Issues of politics associated with altering water prices are also inherent in the selection and implementation of appropriate water price policies (Dinar, 2000). The potential market failures associated with centralized pricing schemes make it an inefficient option for supply augmentation because demand curves are unknown and uncertain. Although fixed price systems use estimated demand curves and long-term supply availability for price selection, the actual water prices selected frequently fail to match the estimated economically efficient price of water, leaving much potential for market failure (Dinar et al., 1997). Also, any substantial deviation from the estimated demand curves will end with the same result, which leaves little room for error in estimations (de Assis de Souza Filho and Brown, 2009).

Market allocation of water is an economically efficient alternative both to pricing schemes and to the priority allocation systems, which leave little room for the flexibility needed under drought conditions. Water markets can reallocate water not only within sectors but also across sectors, as well as on a temporary (spot or rental markets for water rights) or permanent (permanent transfer of water rights) basis. Water markets allow the true value of water to be revealed, which gives incentives for the efficient use of the resource by various users (Dinar and Letey, 1991). The agricultural sector benefits because of the potential for increased profitability in water conservation, which would be desirable due to the flexible system of pricing implemented by the water market. Similarly, the urban sector also benefits because of the increased availability of water for urban use. In the same way, the environmental sector benefits because of the reduced environmental pollution that occurs as a result of deep percolation of pesticides, which would be reduced due to the increase in irrigation technology application and overall water management that water markets encourage (Dinar and Letey, 1990). Finally, water markets allow the planners to shift their efforts from the day-to-day tasks of water pricing and priority

setting to the long-term tasks of monitoring and managing water markets and its associated physical infrastructures. Groundwater markets and water banks have evolved in India, Pakistan and California (Dixon and Moore, 1993; Kolvalli and Chicoine, 1989; Meinzen-Dick, 1996). Water banks operating in California and Colorado in the USA help to save surplus water in wet years and make it available during drought years.

Role of Other Institutions

The government can also utilize subsidies as a method of drought mitigation, which can take the form of loans, rebates or grants. Prior to 1989 subsidies were the primary way Australia ameliorated drought impacts in the agricultural sector, treating drought as a national disaster. Federal loans were granted for livestock carrying and restocking purposes where credit was not available through commercial sectors, and rebates of rail freight and other forms of travel assistance were also given to aid in the conveyance of fodder and water to drought-affected areas, as well as the conveyance of livestock from the drought-affected areas to drought-recovered regions (Botterill, 2003). Unabated subsidizing in Australia to reduce drought impacts under national disaster relief was counterproductive as the government was not able to enhance the sustainability of the agricultural and livestock sectors. Subsidies have also been allotted in pre-1990 South Africa to assist in the maintenance of herds during water scarcity (Wilhite, 2000a). Following 1990, South Africa and Australia adopted new policy measures that removed coverage of drought under National Disaster Relief Arrangements and implemented various relief schemes that encouraged on-farm sustainability and conservation. In South Africa, drought relief was contingent upon adherence to stocking rate standards and other conditions of a conservation farm, while in Australia, aid was distributed to farms that demonstrated a long-term productive future in agriculture under the Farm Household Support Act (Botterill, 2003). The revisions in federal policy in both countries were effective in reducing drought hazards and impacts by reforming policies that once encouraged resource degradation and delayed the onset of impacts into policies that encouraged sustainability and reduced the potential for negative drought impacts.

Another common technique governments use to alleviate the risks associated with drought is crop insurance plans. Farmers have the option of purchasing crop insurance in the event that the onset of drought should cause considerable crop damage and economic loss. Most crop insurance programs cover a portion of the average expected yield and require a deductible for management of adverse selection and moral hazard (Skees et al., 1999). Although crop insurance plans appear to ameliorate the risks associated with drought to the individual farmer, research shows that they may actually perpetuate farmers' vulnerability to drought by giving incentives for unsustainable agricultural practices. Research conducted in New Zealand illustrates the effect of government programs such as crop insurance on the individual farmer's behavior. After the New Zealand government eliminated subsidies in the agricultural sector, farmers no longer engaged in high-risk agricultural practices but instead adopted sustainable ones. Prior to the elimination of government subsidies in the agricultural sector, farmers regularly cleared marginal lands for pasture, used fertilizer excessively and maintained high stocking rates for livestock. Following the removal of these subsidies, stocking rates decreased, crops were no longer grown on lands where risk of failure was high and fertilizer began to be

used cautiously. Farmers also began to diversify crops as well as their sources of income, becoming increasingly self-reliant and better able to cope with the risks and hazards associated with drought.

Besides the policy-related institutions such as subsidies, farm aid and crop insurance, there are also other important agricultural and rural institutions that play a major role in combating the effects of droughts in particular and climate change in general. They relate to the agricultural extension system, farm input supply institutions, agricultural marketing system, trade policies and food storage and distribution system. An effective agricultural extension system is essential in promoting the adoption of various crop and irrigation technologies and farm management and irrigation practices. The same is also true of an effective and flexible farm input supply system that provides timely and cost-effective supply of farm inputs such as drought- and disease-resistant seeds, fertilizer and credit. The agricultural marketing system is important in providing the incentive prices that can promote the adoption of better inputs and farming practices. Since trade policy determines the nature and extent of imports and exports of foodgrains and other agricultural products supporting rural non-farm sectors, they also determine the overall incentive environment for farm production. It is important that the trade policies are well aligned with the prevailing and anticipated production conditions obtained during the drought conditions. The food storage and distribution networks also play a major role in stabilizing year-to-year variations in the supply and availability of agricultural products, particularly foodgrains. Since these networks are also involved in the procurement of key agricultural products, they tend to strengthen the operation of agricultural markets, particularly during drought conditions.

CONCLUSIONS

Most studies in the growing literature on the impact of and adaptation to drought and climate change in the context of agriculture and water sectors focus mainly on the physical, economic and technological dimensions. The research attention to the institutional dimensions has been either tangential or limited. This is not because researchers are unaware of the role of institutions, but because of the analytical and empirical problems involved in treating the institutions within the framework used for assessing the impact of climate change. However, as has been argued in this chapter, the success of most of the adaptation options and coping strategies are critically predicated on the existence of effective and flexible institutional and infrastructural mechanisms. These mechanisms cover not only those related to the agricultural and water sectors but also to those related to other macroeconomic policies such as trade, crop insurance and disaster relief. This chapter has developed an analytical framework and a system model that captures the explicit role of various institutions and infrastructures.

Despite the abstract and aggregate nature of the analytical framework and the model, the chapter has also made explicit the central role of the institutional and infrastructural aspects in the impact generation and transmission processes operating between the initial impacts of climate change and their final effects on the ultimate goal of economic welfare. In this sense, the chapter has also demonstrated how important are the

institutional and infrastructural factors in the adaptation of the agricultural sector to the potential impacts of climate change and drought. While technologies and farm management practices are used directly to counter the climate change and drought impacts, institutions provide the necessary economic incentives for their development and widespread application at the farm or local level. Infrastructural factors, on the other hand, provide the physical framework for the operation of institutions as well as the provision of inputs, procurement of farm outputs and augmentation of resources such as land and water.

Although the empirical application of the model was not the objective of this chapter, it has outlined, however, the empirical issues, including the role of stakeholder-based subjective data, involved in the practical application of the analytical framework and the system model. While the empirical aspects of most impact pathways depicted in Figure 21.1 and captured in the system model are clear, there is need for further clarification in the first part of Figure 21.1, which covers the role of the four adaptation mechanisms, that is, science and technology, adaptive farm management, water infrastructures and water institutions. As is clear from the anecdotal evidences provided for the role of these four mechanisms, multiple options are involved in each of the four adaptation mechanisms. However, in the specification of the system model, these four mechanisms are captured respectively by four individual variables. There will be questions as to how the multiple options involved in each of the four adaptation mechanisms can be incorporated within such a model. One approach to resolve this issue would require the estimation or the simulation of the model by considering various configurations involving four options representing respectively the four adaptation mechanisms. The exercise would then involve the selection of the adaptation configuration that minimizes the negative impacts of climate change or drought. In this sense, the ideal configuration of adaptation options selected will be the same as that identified through an optimization exercise performed within an *ex ante* context.

NOTE

1. See Saleth and Dinar (2008, pp. 11) for demonstration of the derivation of the chain equation and Saleth and Dinar (2004, pp.359–65) for the calculation of the total impact of the institutional variables.

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22 Conclusion and future research

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This *Handbook on Climate Change and Agriculture* presents the views of experts from around the world and from several disciplines. There are some convincing conclusions that follow from this collection of writings. First and foremost, climate change is expected to have an extensive impact on agriculture around the world. Every farmer in the world will be affected directly by changes in temperature and precipitation, and by changes in concentrations of carbon dioxide. Farmers who depend on irrigation may also see changes in available water flows. As aggregate changes affect markets, there will be additional indirect effects from climate change felt through changes of prices of inputs, land and food. Price changes in turn will again affect farmers, but also consumers of food. Finally, there will be mitigation efforts from climate policy that involve farmers and that might affect the availability of land and water. One conclusion that seems to echo in every chapter is that climate change will affect agriculture. Another important conclusion across methodologies is that damages will tend to be more severe in the low latitudes than in the middle to high latitudes. This is partly because climatic conditions in the lower latitudes tend to be hot and dry already, and because low-latitude farms may have other constraints that compound climate problems such as lack of infrastructure, poor governance and weaker property rights.

Every discipline represented in this *Handbook* has something to contribute to our understanding of the effect of climate change on agriculture. From laboratories to field experiments, agronomists have studied how temperature, precipitation and carbon dioxide (CO₂) affect crop yields. Crop models have been built to understand how all of these factors are linked to the yields of important crops. Economic models have been built to understand how changes in yields would affect farm decisions, markets and welfare. Economists have studied farm outcomes in different weather conditions over time to measure how the variation in weather affects yields and net revenues. Economists have also studied farm outcomes in different climates across regions taking into account ecosystem effects as well as farm adaptations. Trade and macro models explore how changes in the agricultural sector affect global outcomes and the broader economy. Mitigation policies may also affect agriculture by influencing energy prices and the availability of land and water. Finally, economists have studied adaptation. How will farmers adapt to changing climates? What will they do in each local setting? How does this change climate impacts to the sector?

CONCLUSIONS OF INDIVIDUAL CHAPTERS

Controlled experiments provide the foundation for understanding how climate impacts agriculture (Chapter 2). Laboratory and field experiments have tested how individual crops fare under different levels of temperature, precipitation and CO₂. Every crop has a

specific climate range where it grows best. Crop yields appear to have a hill-shaped relationship with temperature and precipitation. Consequently, crop yields for existing crops will probably improve in locations that are too cool and decline in places that are too hot for that crop. For some crops, there appears to be a maximum temperature above which yields fall dramatically (Schlenker and Roberts, 2009). Similarly, if a location is already too dry (or wet), reductions (or increases) in precipitation will make matters worse. However, if a location is currently too dry (or wet), then increases (or reductions) can help offset some of the deleterious effects of warming. Similar effects can be seen on rangelands. Furthermore, pests, weeds and disease will also respond to climate change and have indirect effects on farmers' decisions and welfare.

In addition to being a greenhouse gas, CO₂ directly affects plants (Kimball, 2011). Higher ambient CO₂ levels directly fertilize plants and allow them to shrink their stomata openings. This helps plants tolerate high temperatures and have higher yields. Both laboratory and open field experiments suggest CO₂ fertilization leads to 10–45 per cent increases in C₃ crop yields. These gains will offset some of the losses anticipated from temperature and precipitation changes. However, CO₂ fertilization benefits will not be felt uniformly. Tropical grasses and C₄ plants barely respond to higher CO₂. The CO₂ fertilization effect is smaller if crops are constrained by poor soils. The increased yield from CO₂ may not be accompanied by an increase in proteins and minerals. Finally, CO₂ fertilization may also increase problems from weeds and pests.

Climate not only affects crops but also livestock (Chapter 3). Impacts on livestock are important because livestock accounts for 40 per cent of agricultural GDP (World Bank, 2007). Climate can directly affect livestock by affecting health, growth, reproduction and mortality. Climate can also indirectly affect livestock by changing feed prices, forage (rangeland) and disease vectors. The best-known impact of climate on livestock is thermal stress. Thermal stress is known to reduce growth and increase illness prevalence. A temperature humidity index has been developed for animals to measure effects on growth and health. The optimal climate in regards to temperature and humidity for specific animals varies as species and breeds are adapted to very different climates. The sensitivity of livestock to climate also varies depending on whether the animal is sheltered or not. The temperature and humidity pertinent to indoor animals is that of the indoor conditions. Because they are sheltered, livestock in developed countries are less sensitive to climate. To control indoor temperatures, farmers may need to improve ventilation or resort to cooling methods such as spraying. This increases the energy cost of raising livestock but protects the livestock from the direct effects of climate. Animals in developing countries generally lack shelter and so are exposed more directly to climate. Furthermore, climate has indirect effects, especially on developing-country animals through changes in forage. CO₂ fertilization may lead to a reduction in pastureland quality as C₃ plants more effectively compete with C₄ grasses, which are preferred by livestock. Climate change may also allow livestock diseases such as bovine respiratory disease and blue tongue to spread to new regions. Finally, higher temperatures will increase the water needs of livestock. Water consumption can double in higher temperatures.

Agronomists have developed three basic tools to study the interaction between climate and crops (Chapter 4). Climate indices have been empirically estimated based solely on climatic variables to predict the distribution of crops and their yields. The absence of economic incentives in these indices makes them of limited use, but they do suggest

that crop choice is linked to climate. Agronomists have also constructed process-based crop models of the major crops in the world. For example, DSSAT is a decision support system to analyze multiple crop yields and management strategies. EPIC is a system of simplified growth functions for individual crops. Models have also been developed to predict water demand for irrigated crops under different conditions. Each of these models has been calibrated to a number of different locations around the world including the OECD countries as well as countries in Africa and Asia. For climate change predictions, the models are sensitive to whether they adequately capture climatic variability and whether they apply when climate deviates from observed levels. Another hurdle for these models is to predict impacts across a wide spatial scale from a limited set of precise point estimates. Another limitation is that the crop models assume there is no response by weeds and pests to climate change. Each of these limitations has been addressed in specific studies which show that they can be important. Economic impacts have sometimes been estimated from crop model outputs by multiplying changes in yields by prices. However, such estimates assume that there are no endogenous adjustments to changing conditions by either farmers or markets.

In addition to adjusting to changes in mean temperature and precipitation, agricultural systems must also adjust to drought and temporary weather conditions, leading to insufficient soil moisture (Chapter 5). Drought is caused by some combination of high temperatures resulting in higher than normal evapotranspiration and low precipitation. With higher future temperatures, droughts may well become more common. Unlike other sudden extreme events such as storms, droughts typically creep into existence as a result of cumulative abnormalities. However, like storms, droughts strike worldwide with little forewarning. One way of coping with droughts is to develop risk management strategies that improve drought detection, provide alternative crops and animals for farmers to select in drought conditions, and manage water resources more carefully. These management strategies can help farmers cope with future droughts, especially if they become more severe in the future.

In order to obtain an accurate measure of the welfare effects to agriculture, the basic agronomic predictions from crop models must be incorporated into economic models. For example, mathematical programming models can utilize the change in yields predicted by crop models within an overall market economy to simultaneously predict the resulting endogenous price and crop choice of each farmer. Such sophisticated models of entire markets are very data intensive and have been built only for the USA (Adams et al., 1990, 1999). Further, these market-level models capture only a limited adaptation response by farmers.

Farm-level models have been developed to explore more of the detailed choices of farmers. These models were originally focused on evaluating only the changes in mean temperature and precipitation at a specific farm. However, farm-level models have recently been expanded to capture weather variability (Chapter 6). Climate change is represented as moving from one weather distribution to another. Expected value or passive programming has been used to measure farm profits in each weather outcome. This approach assumes that farm decisions can be optimized once the weather is realized. If some decisions must be made in advance of full information, stochastic programming can determine optimal strategies to follow under uncertainty. A discrete sequential programming approach combines these two approaches by assuming some decisions must

be made in advance under uncertainty, whereas other decisions can be made once the uncertain factor is realized. Of course, these depictions of uncertainty become increasingly difficult to model with complexity. The model applications consequently tend to focus on limited choices. One of the conclusions of this new literature is that it is more difficult to adapt under uncertainty. Deterministic models may overestimate the effectiveness of adaptation actions by farmers.

Another approach to understanding the impact of climate change on farms is through direct empirical estimation of the link between net revenue per hectare and weather. Deschenes and Greenstone (Chapter 7) use an intertemporal panel approach to regress net revenues on weather variation using US panel data. The technique uses fixed effects to control for the characteristics of farms. The fixed effects have the desirable consequence of controlling for unmeasured characteristics of each farm. However, the fixed effects also control for desirable information about the role of climate. For example, with the fixed effects, it is not possible to tell whether the effects of high temperatures are different for farms in cool versus warm locations. The study also introduces some intertemporal control variables such as state-weather effects that eliminate meaningful variation in weather variables. By overcontrolling for weather, the authors underestimate the importance of weather in their analysis. Although this particular application of the methodology has limitations, the intertemporal analysis of panel data is a promising approach for measuring the sensitivity of farms to weather. Panel data can also be used to measure the sensitivity of farms to climate (Chapter 8). Farmland values can be regressed on climate (not weather) by relying on the cross-sectional information in panel data. This Ricardian approach (Mendelsohn et al., 1994) has the advantage that it controls for long-term differences in climate from place to place. This includes long-term ecosystem adjustments to climate such as pests, weeds and disease changes, as well as adaptation efforts by farmers. Of course, the Ricardian approach remains vulnerable to unmeasured variables correlated with climate. This specific example from the USA relies on repeated cross-sectional regressions following Deschenes and Greenstone (2007). One limitation of this approach is that it does not take full advantage of panel data methods. However, the chapter makes a number of improvements over the earlier Deschenes and Greenstone (2007) study. The analysis corrects the measurement errors in the climate data, adds omitted observations and more explanatory variables, and improves the functional form. These changes improve the fit and the robustness of the resulting regressions. The study finds that climate change is likely to increase farmland values in the USA, but the effect varies by region, with northern and central states receiving the bulk of the benefits. The analysis also reveals the importance of precipitation and seasonal effects.

Because the agricultural sector is a large part of GDP in many developing countries, what happens to agriculture can affect the entire economy. It is therefore interesting to explore what impact changes in the agricultural sector will have on the rest of the economy. Starting with a spatially detailed agricultural model (IMPACT), Calzadilla et al. (Chapter 9) use a general equilibrium model (GTAP-W) to measure economy-wide consequences. The authors take special pains to separate pasture, rainfed and irrigated land in this model of the entire world. Examining a Hadley climate forecast of a modest emission scenario out to 2050, the model examines what happens to global agriculture, but especially sub-Saharan African agriculture. The model predicts a 15 per cent reduction of irrigated crop production because of reduced runoff, and a 0.7 per cent reduction

in rainfed production in sub-Saharan Africa. Without adaptation, food production will fall 1.6 per cent, increasing malnutrition in 2 million children. However, with adaptation, food prices fall and malnutrition falls in Africa, according to the model. One of the constraints with global general equilibrium models is that the authors must make many simplifications to build the model. For example, the authors assume that the world is perfectly competitive, an assumption that probably does not apply to the common-property water and lands in many developing countries. The authors are also constrained by data limitations, making many parameters of the model hard to estimate.

The next chapter explores how agriculture is depicted in integrated assessment models (IAMs) of greenhouse gases (Chapter 10). IAMs are designed to combine the information about the manmade sources of greenhouse gases, the geophysical–climate consequences of different emission paths and the final impacts of climate changes into a cohesive model that can evaluate the costs and benefits of global climate policy. With such a weighty task, the models tend to have very reduced-form descriptions of individual sectors. For example, agriculture is treated as an exogenous source of emissions and merely a component of an aggregate damage function in the first IAM (DICE) (Nordhaus, 1991). More detailed IAMs have an explicit land base in their climate–geography system but these natural science components generally do not include endogenous responses by human management. A few IAMs (such as IMAGE and GCAM) explicitly capture the competition for land between agriculture and forestry so that mitigation activities such as deforestation, reforestation and biofuels can be modeled. However, these land-use models currently treat deforestation and investments into more intensive agriculture as an exogenous, not an endogenous, response. The IAM presented in this chapter – REMIND-MAGPIE-LPJmL – attempts to overcome this limitation by allowing investments in the land sector to be endogenous. The authors find that a massive global bioenergy program could lead to substantial deforestation. However, if forests were conserved the bioenergy program would drive up food prices, encouraging significant investments in agricultural intensification. Yield productivity per hectare would consequently increase, reducing the final food price effects. Even if IAMs do not contain a land-use module, several of them (such as PAGE and FUND) have explicit impact equations for regional agriculture so that they can predict differential impacts from warming to agriculture in each region. However, there remain questions about how well IAMs capture adaptation.

Climate change is predicted to have different impacts in different regions. Trade is an important adaptation that helps mitigate the welfare effect of climate change on local regions (Chapter 11). As countries trade with one another they can balance out gains and losses in different regions. This provides a form of insurance to consumers. Prices for food and therefore food consumption would depend on global production instead of local production. Since global production is far more robust than local production, trade will help the world adapt to climate change. For example, climate change is expected to change average yields in different regions, with some production increasing and some production falling. Areas with consistently lower yields can recover lost consumption by importing food. Similarly, areas that have increases in production can export food. Trade provides protection against long-term local changes in food production. It also provides protection against short-term effects caused by annual weather. In bad years countries can import from other regions that did not experience the same weather. Trade provides

an important form of climate and weather insurance for consumers of food. Of course if global production changes, world prices will also change and trade implies that consumers and producers will be affected everywhere. If global production falls (or rises), prices will rise (or fall), benefiting (or hurting) farmers and hurting (or benefiting) consumers. Local impacts on farmers would depend on the combination of local changes in production versus global changes in prices. That is, climate impacts on farmers would depend upon how they fared relative to other farmers in the world. It is generally expected that climate change will increase the productivity of farms in middle- to high-latitude regions this century but reduce the productivity of farms in low latitudes. This will lead to a net benefit for middle- to high-latitude farms and a loss to low-latitude farms.

Farms may not only be affected directly by climate change, they could also be affected by mitigation policies aimed at reducing greenhouse gases. For example, one mitigation strategy is to subsidize biofuels so they can substitute for fossil fuels and therefore curtail greenhouse gas emissions (Chapter 12). For countries with substantial farmland and insufficient fossil fuels, the biofuels program also offers the carrot of self-sufficiency (independence from foreign oil). But the biofuel strategy has other drawbacks. If low-productivity lands were used to grow bioenergy, the program would require extensive amounts of land to produce energy. A great deal of the energy from the program would be needed just to collect and process the plant material from across the landscape. The net production of such a system would be low, making the biofuel expensive. If more productive agricultural lands were used (as with US corn ethanol, Brazilian sugar cane ethanol and Indonesian palm oil), the program would greatly increase the demand for agricultural land and therefore place enormous pressure to increase the supply of farmland. The biofuels program would lead to a substantial increase in deforestation. This would release substantial amounts of carbon that reduce the impact of the program as a greenhouse gas mitigation tool. Finally, if forest land were completely protected to avoid deforestation effects, the biofuels program would sharply increase the price of farmland. This would cause high food prices and food shortages around the world. A large-scale biofuels program has the risk that it could have more severe effects than climate change. Second-generation biofuel systems can take advantage of the entire plant and therefore potentially reduce some of these drawbacks, but no viable technology has yet been developed.

One tool to encourage countries around the world to reduce greenhouse gas emissions is the Clean Development Mechanism (CDM) (Chapter 13). Wealthy countries or international aid agencies can subsidize individual projects to reduce greenhouse gas emissions in developing countries through CDMs. CDMs at present are primarily targeted at the energy sector. Less than 1 per cent of the CDM projects pertain to agriculture. This low level of investment into agriculture is a surprise given the low-cost mitigation potential alleged in this sector by the IPCC (IPCC, 2007). Farmers can grow biofuels, change tillage practices, intensify production on cropland and pasture, and manage animal waste to inexpensively reduce agricultural emissions of greenhouse gases. Only the production of biofuels is actively pursued in CDMs. One reason why CDM may not be financing agriculture projects is that it is harder for these projects to prove additionality (a net change in emissions). The land-use projects are also long lived, and so questions of reliability are prevalent. The land-use projects are also vulnerable to leakage as most emitters remain outside the CDM framework and may well adjust their behavior in response to CDM project behavior. Finally, another limitation is that 79 per cent of

CDM projects occur in just five countries, as many developing countries do not have the resources and expertise to qualify for CDM. Some of these limitations can be addressed by streamlining the administrative process required to qualify.

The research on climate impacts on agriculture indicates that farm adaptation can potentially play an enormous role. Without adaptation, climate change is likely to damage most farms. However, if farmers adapt as climate changes, the net harmful agricultural impacts of climate change will be substantially reduced and may sometimes turn into a net benefit. Will farmers in fact adapt? Aisabokhae et al. (Chapter 14) provide an eloquent general discussion of farm adaptation and note that farmers will adapt because it is in their own interest. Farmers will change their crops and livestock and farming methods as climate changes because it will increase their profits to do so. In fact, there is strong evidence that farmers have been actively adapting to weather- and climate-related phenomenon for decades if not centuries. By comparing farm outcomes across climate zones, it is apparent that farmers have adjusted crops, species, varieties, pesticide management and timing to match their local climates. Furthermore, models of individual farms and especially US farm markets suggest profitable adaptation options. For example, the FASOM model suggests that climate change would induce substantial shifting of crops across the country (Adams et al., 1990, 1999).

Another important climate adaptation concerns modifying how water is delivered to farms (Chapter 15). This chapter examines the complex water systems that deliver irrigation water to California farms. If no changes are made in the system, underlying changes in the hydrology will lead to substantial shortfalls in water supplies to many farmers (Smith and Mendelsohn, 2006). Runoff will decline along several rivers and flows will shift to late winter–early spring prior to when they are needed. The shift to earlier flows can be addressed with construction of high-altitude dams that delay the supply of water to match demand. The changes in the level of flows can be addressed by reallocating water from low- to high-valued uses. By moving water to high-valued fruit and vegetables and away from low-valued pasture and fodder, the system of dams and canals can be managed to minimize the damage to Californian agriculture from all but the most severe water shortages. The analysis provides strong support for the importance of adaptation in the water sector in regions that depend on irrigation.

The importance of irrigation as an adaptation strategy itself is explored by Fleischer and Kurukulasuriya (Chapter 16). The analyses explore how irrigation in Africa and Israel has allowed farmers in both regions to adapt to hot and especially dry conditions. In addition, farmers in Israel have adopted cover as an additional protection against intense heat. Provided there are adequate water supplies, irrigation allows crops to endure higher temperatures and less rainfall. Farmers can then turn to irrigation and cover as adaptation strategies to climate change. In fact, in climate change scenarios that entail increases in precipitation, there is a marked projected increase in irrigation in Africa. Furthermore, as Israel has demonstrated, an effective response to reduced water supplies is to shift towards more expensive but water-efficient drip irrigation systems that allow even limited water supplies to contribute to large areas of high-value crops. The analysis in this chapter also provides the technological envelope for what African farmers can reach in the future.

Another longer-term adaptation comes from technological innovation (Chapter 17). There are two different strategies to adapting to climate change. One strategy involves

changing technology to be more suited for a warmer, higher CO₂ climate with either more or less precipitation. Another strategy is to simply intensify production in ideal locations (across-the-board improvements) to make up for lost production in areas that become less suitable. In practice, both strategies should be followed. A well-known source of crop and animal productivity increases has come from advances in genetics, including not only traditional breeding but also genetically modified crops (GMOs) and animals. These new seeds and breeds have higher yields and sometimes lower costs of production. Genetic advances are not only expected to continue to raise yields across the board but could also be designed to specifically adapt to high temperatures, drought conditions and higher CO₂ levels. Unfortunately, making genetic improvements in plants to be more productive in hotter and drier climates is not easy, as there are not single genes for climate adaptation. Scientists will have to modify many aspects of the genetic sequence to develop more productive plants for different climates. Finding modifications that both make a plant more robust as well as more productive is a challenge. However, genetic improvements have not historically been the only source of rising productivity. Looking to the future, genetic improvements may not even turn out to be the most important source of adaptation from technology. Improved management techniques could actually be a more effective source of adaptation. There is still a substantial gap between actual performance and potential performance for most farms. Choosing the right crops and varieties and the right animals and breeds for each local condition is one very important task. Optimizing growing conditions for animals and applying inputs such as fertilizer and water more deftly across cropland could both increase output and lower costs for both farmers and local ecosystems. The use of controlled environments such as cooled sheds for animals and greenhouses for plants may become even more widespread for high-valued products. There is also substantial room to improve pest and weed management on farms from careful application of improved chemicals. Improved machinery could lower costs and increase profits. These management adjustments could prove to be far more important than new genetics in the long run.

One reason that the CGIAR system can be so useful to developing countries is that it can focus on agricultural systems that are unique to developing countries, such as mixed crop–livestock farms (Chapter 18). Mixed crop–livestock farms cover 2.5 billion hectares. In the absence of capital and insurance markets, mixed systems help small farmers in developing countries obtain more robust outcomes. In years when crops do poorly, livestock can provide needed revenue. In good years, crops can provide higher income. Mixed systems often take advantage of interactions between crops and livestock. Livestock can provide the power for tilling, animal waste can be a source of nutrients for the fields, and crops and crop residues can be a source of feed for the animals. Of course, doing many things on one piece of land prevents farms from specializing. As farms become more intensified, they tend to shift out of mixed systems. One advantage of mixed systems is that there are more substitute activities for the farmer. As the climate dries (or moistens), the farmer can increase the livestock (or crop) percentage of the farm. As temperatures rise, the farmer can shift not only crops but also livestock in response. Similarly, the systems are also quite agile in adjusting to an increase in weather variability. In the long run, farmers may be able to intensify production, find a wider array of crops and animals to choose from, and choose combinations of crops and animals that are even more robust. And of course, another well-known adaptation is that

small farmers also look for off-farm work as a protection against periods when weather is particularly hostile. At the extreme, if climate becomes too hostile, farmers may have to rely on off-farm work for most of their income. If poor conditions persist, farmers clearly will consider whether pulling out of agriculture and migrating to more productive locations or cities would make them better off.

Another form of adaptation is crop insurance (Chapter 19). Crop insurance remains largely a government activity because governments can offer subsidized insurance which private insurance firms cannot compete with. That is, public crop insurance programs have lower premiums (revenues) than payouts (costs) and therefore require consistent public support. In addition to requiring public funds, public crop insurance programs are also inefficient. They tend to charge the same premium to all farmers even when risks are not uniform. Farmers in risky locations therefore pay a smaller fraction of their long-run cost than farmers in safer locations. Farmers in risky locations receive a larger subsidy to stay in harm's way. This feature of public insurance programs increases agricultural damages from weather events, which is a maladaptation and may exacerbate conditions. For insurance to be considered a climate adaptation tool, local premiums must be equated with future expected risks. Another concern with all insurance programs is the extent of catastrophic risks. Single events such as the most powerful hurricanes can lead to substantial damages that are more than what one company could bear to insure against. However, the share of these extreme event risks that pertain to crops is quite small. Crop insurance will generally not need catastrophic risk coverage for extreme events with the possible exception of large-scale droughts. Nonetheless, as the climate gradually changes, the cumulative damage to the global agricultural system could become quite large. If insurance companies provided term insurance guaranteeing farmers protection decades in advance, they would need catastrophic insurance. It is not likely that such long-term insurance contracts will ever be underwritten. Furthermore, they would be another example of a maladaptation. Long-term insurance would discourage farmers from adapting over time since the insurance company would pay for all losses. More likely, the sole purpose of crop insurance will remain protecting farmers against annual weather. Climate change still has two important influences over weather insurance. First, it may alter the distribution of weather, making it either less variable or more variable. Second, it may alter the long-term productivity of farms. Both factors will change the risks and therefore the premiums that insurance companies will need to charge to balance the long-term budget of the program. Insurance companies will therefore have to remain vigilant as the climate changes. They must be careful to set premiums based on the current climate and not rely on dated historical evidence. The authors demonstrate that the needed changes in premiums over a century in one climate scenario could be quite large across the Iberian Peninsula.

One of the important adaptations that farmers must consider is optimizing their choice of livestock to fit local climate conditions (Chapter 20). Although many authors talk about livestock choice as an important type of adaptation, very little is known about the sensitivity of livestock choice to climate. By estimating a formal econometric model of livestock choice across climate zones, it is possible to discern exactly what role climate plays in this important adaptation decision. This chapter examines livestock choice across two samples of farmers from Latin America and Africa. The study estimates the likelihood that farmers will choose whether one out of the five most important animals

in each continent will be the primary revenue-earning animal on their farm. The choice of each animal depends on current local climate conditions. If these relationships continue to hold in the future, African farmers will shift away from beef cattle and dairy cattle and towards sheep and goats as temperatures rise. South American farmers will also shift away from beef cattle and dairy cattle and towards sheep as temperatures rise. These shifts in livestock choice will help farmers maintain their net revenues in the face of climate change.

A final set of important adaptations requires institutional changes (Chapter 21). Rather than investing in bricks and mortar (hard adaptations), institutional changes (soft adaptations) alter the setting in which choices are made. In places where current institutions are performing badly, institutional changes can be highly effective agents of change. However, institutional change needs to be aware of effects between one agency and another. For example, water and agricultural agencies must coordinate. It is also true that local, state and national institutions must coordinate. Finally, policies can have effects on one another. If a systemic approach is not taken, policies can sometimes work in opposite directions and cancel each other out. There are many reasons to consider institutional change, so that it can often be argued that institutional changes would be beneficial even if climate does not change. For example, the chapter on water allocation (Chapter 15) stresses the importance of allocating water efficiently as an adaptation to climate change. However, improved water allocations would improve current conditions as well. Existing government water institutions currently dominated by engineers and hydrologists could be fortified with economists to assist in better water allocation methods. Alternatively, water markets could be established that allow high-valued water users to purchase water from low-valued users. A great deal of agricultural land in developing countries is common property and is poorly managed. Local governments could develop stronger administrative skills to manage local common-property land more efficiently. Alternatively, common-property farmland with high productive capacity could be privatized to unleash competitive forces to invest into and manage these lands more efficiently. Similarly, inadequate R&D efforts could be subsidized and supported country by country. Alternatively, international efforts could be funneled into specialized agencies (FAO or CGIAR) to provide direct technical assistance. In principle, one could estimate technical models that include institutional variables as explanatory factors for inputs yields, and net revenue. In practice, such models are difficult to estimate because of missing data and the convoluted linkages between institutions and all of these dependent variables. Empirical proof of the efficacy of institutional changes is therefore lacking despite the support such changes have from theory.

FURTHER RESEARCH NEEDS

It is clear from this *Handbook* that a great deal of research has been completed on the impact of climate change on agriculture across the world. Although a great deal of the agriculture in the world has now been studied, there still remains much more to do. Climate impacts on the world's most important crops and animals are largely understood, but many crops and animals have never been studied. Many studies have been conducted on some regions of the world such as the USA, but few studies have been

conducted in other locations. In fact, there are hardly any impact studies in the Pacific islands and the former Soviet Union.

One concern raised in the literature is that some government programs encourage maladaptation. If there is a great deal of maladaptation, impacts will be even more severe. Well-intentioned programs such as public crop insurance and disaster relief have the unfortunate consequence that they encourage farmers to stay in harm's way. Trade barriers that prevent food from freely moving between countries make countries more vulnerable to local weather events and long-term climate change. How to reduce the undesirable consequences of such programs is an important topic for new research.

As farmers adapt, they can endure larger changes in climate. This *Handbook* presents many chapters on climate adaptation. Past studies note that adaptation is a local phenomenon. Each local area needs a different strategy given their local conditions, and each area must find a different strategy depending on how climate actually unfolds. However, adaptation research is a relatively new field. Many places have not yet been studied. Past studies have quantified only some of the decisions that farmers must change as climate changes such as crop choice and animal choice. But additional work is needed to explore all the best adaptation strategies for different climate outcomes and different locations. How should farmers change planting and harvesting dates? What new varieties make sense for different places? What other management choices need to be adjusted to new climates in each place?

There is a need for new research to come from both public and private resources. Public investments into basic research can be more readily shared and so capture the public-good quality of new ideas. However, public agencies have a very poor record of delivering applied research as they are often indifferent to the profit motivation of farmers. Private firms have generally been more effective at bringing ideas to market. There is consequently an ideal mixture of public and private investments into R&D that takes advantage of the strengths of both institutions to support technological advances. Whether these future advances will be applied to developing countries remains a serious policy issue because of problems with property rights, technological transfers and capital constraints. International support for research and development centers targeted at developing countries (the CGIAR system) remains an important vehicle to overcome these barriers.

As institutions and governments adapt, the world can increase the overall efficiency of the entire food system. Although there is every reason to believe that farmers will adapt because it is in their own interest, it is less clear that governments will adapt. Yet it is quite apparent that improving the efficiency of agricultural and water institutions will be important. Additional research exploring how to make institutional changes meet new climate challenges is needed. What can be done to improve the performance of critical governmental institutions managing public land and water? How can governments at each level, from local to international, be harnessed to address adaptation effectively?

Another critical factor in the long run is the rate of technical change in farming. Farming productivity has been increasing at roughly a 2 per cent annual rate for the last 100 years. This has caused food prices to decline for a century. If such baseline productivity increases can be maintained into the future, the productivity increases can offset productivity losses from climate change. Global food supplies will be sufficient to feed future populations. However, for such increases to be maintained it is important that

new crops and breeds continue to be developed. It is also critical that improvements in farm management continue to spread worldwide. If farmers can adopt optimal input and management strategies, they will be able to sustain large improvements in both productivity and environmental outcomes.

Finally, climate policies aimed at mitigation can have large impacts on agriculture even in the absence of climate change. The general equilibrium effects of mitigation need to be better understood. For example, efforts to remove CO₂ emissions from the energy system will probably make energy very expensive. Not only is energy an important direct input into farming, it is also critical to making fertilizers. What are the consequences to farmers of aggressive mitigation efforts in the energy sector? Large-scale programs to grow biomass crops could also have enormous influence on the agriculture sector. Massive bioenergy programs to replace fossil fuels would substantially increase the demand for cropland. This could lead to substantial deforestation as the global market responds by expanding cropland. If efforts to expand cropland are constrained by an effective global forest protection program, farmland prices will rise rapidly. This will make any large scale biomass program very expensive. It could also substantially increase the price of food with all the malnourishment consequences currently being attributed to the worst climate scenarios. Additional research exploring the magnitude of these effects is clearly needed.

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